Current Assessment of the Benefits of Recycling in Thermal Reactors

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ABSTRACT

This report summarizes the potential benefits of recycling the transuranic elements recovered from used Light Water Reactor (LWR) nuclear fuel into thermal-spectrum reactors. The report considers how thermal recycling might be useful, when, and why. This requires identifying potential roles for thermal recycling, as opposed to the other two major classes of alternatives – no recycling of any kind (once-through fuel cycle) or recycling only in fast reactors. The potential benefits of recycling in thermal reactors are assessed against the goals and objectives of the Advanced Fuel Cycle Initiative (AFCI) and now the Global Nuclear Energy Partnership (GNEP). The report explains the goals, objectives, and metrics for assessing fuel cycle benefits, followed by the range of fuel cycle options assessed. The report then analyzes potential thermal recycle benefits via steady-state or equilibrium analyses for a broad range of options and via time-dependent or dynamic analyses for the five most prominent options. Finally, the report summarizes conclusions and lists additional work that could be done to resolve key issues. Appendices describe the difference between thermal and fast reactors, which chemical elements should be separated and recycled, and the key parameters used in the dynamic analyses.

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EXECUTIVE SUMMARY

Introduction

Recycling of transuranic elements (see sidebar) from the used nuclear fuel from light water reactors (LWRs) is technically feasible and has several potentially attractive attributes.

Fuel cycle strategies utilizing recycling in LWRs can be developed with or without concurrent recycling in fast reactors. The recycling in LWRs can be for a single pass or done repeatedly. In general, there are several possible roles for LWR recycling, as follows:

1. **Stop-gap recycling** – One recycle pass in thermal reactors followed by subsequent recycle in fast reactors.
2. **Mixed recycling** – Recycling with a symbiotic mix of thermal and fast reactors.
3. **Backup recycling** – Recycling in thermal reactors if economic or acceptance problems develop with fast reactor recycling.
4. **Pure thermal** - Thermal reactors as the only planned mechanism to recycle used fuel.

This report was requested to examine potential benefits of recycling in thermal reactors. It is not intended to create new specific recycling scenarios nor to address the status of required technologies.

Hypothetical delays in fast reactor deployment are postulated in some portions of this report to explore potential benefits of recycling in thermal reactors. Nothing in this report is intended to imply that such delays are likely or desirable.

Fuel Cycle Strategies

Analysis of fuel cycle options compares four possible strategies – once-through, thermal reactors only, a mixed thermal-fast fleet, fast reactors only.[DOE2006, DOE2007] Two of these four strategies include recycle using thermal reactors.

The first is recycling in thermal reactors only, designated as the "pure thermal" role for thermal reactors. Uranium in used fuel and depleted uranium would be stored for future reuse as fuel or disposed as low-level waste. Transuranic elements would be recycled in LWRs, thereby transmuted into fission products and energy (via fission) or into heavier transuranic isotopes (via neutron capture). Residual transuranic elements from processing losses would go to geologic disposal. Long-lived fission products would also go to geologic disposal. Targeted short-lived fission products would be first stored to allow for radioactive decay and ultimately disposed of as low-level waste.

- One variation is to plan to recycle once and then stop; analyses indicate that this accomplishes few objectives.
- The other variation is to recycle repeatedly; analyses indicate that there are inherent performance limitations associated with such repeated recycling in thermal reactors.

The second is sustained recycle with a symbiotic reactor fleet of thermal and fast reactors. Thermal reactors supply transuranic elements. Transuranic elements are recycled until destroyed. Recycling is either done in only fast reactors or in a mix of thermal and fast reactors. The accumulation of transuranic elements during repeated recycle passes is controlled and limited by fast reactors serving as transuranic element burners. Essentially no transuranic elements would go to geologic disposal, except processing losses. Uranium and fission products would be disposed of as with thermal recycling.

- One variation is that recycled transuranic material is only used in fast reactors; this is the GNEP approach. The fleet contains both thermal and fast reactors. The thermal reactors do not recycle; they are the source of the transuranic material for the fast reactors.[1]
- Another variation is that recycled transuranic material is recycled in both thermal and fast reactors. One can use a mixed recycle approach (recycle in both thermal and fast reactors) for an extended period of time. Or, thermal recycle can be considered a back-up to the GNEP approach.

Two technological approaches to recycling transuranic elements in LWRs are considered in this report – MOX fuel is a mixture of uranium and one or more transuranic elements. IMF means "inert matrix fuel", which is fuel that lacks uranium but includes one or more transuranic elements. Eliminating uranium from the fuel means that no new transuranic elements can be created, but it also means that the chemical matrix of the fuel must be based on something other than uranium. This requires finding an alternative matrix material that, like uranium, is sufficiently easy to chemically separate but sufficiently stable to give good fuel performance. This search has proven difficult.

While there is considerable experience for MOX-Pu fuel and limited experience with IMF-Pu, MOX-TRU and IMF-TRU have both been judged to be at the same low level of technology readiness [DOE2006] because both technologies involve fabrication with americium and curium, which is a substantially different challenge than MOX-Pu or IMF-Pu.

Results with regard to the four potential roles for thermal recycle

Thermal recycle provides several potential benefits when used as **stop-gap, mixed,** or **backup** recycling to recycling in fast reactors. These three roles involve a mixture of thermal and fast recycling; fast reactors are required to some degree at some time. Thermal recycle can also provide some benefits when used as **pure thermal recycling**, with no intention to use fast reactors. However, long term, the pure thermal recycling approach is inadequate to meet most objectives.

Stop-gap recycling – One recycle pass in thermal reactors followed by subsequent recycle in fast reactors. This accommodates potential delay of fast reactors by one or two decades, while still starting sustainable recycling of used fuel. Thereafter, the one recycle pass in thermal reactors would be phased out. Recycling can start to consume transuranic material (far faster with IMF than MOX). The rate of consumption is controllable by the amount of IMF or MOX

[1] The "pure fast reactor" strategy is not addressed in this report. It means that thermal reactors are phased out; the fast reactors must therefore operate in breeder mode.

deployed. Implementing IMF approaches require solving difficult separation and fabrication issues, which are beyond the scope of this report.

Mixed recycling – Recycling with a symbiotic mix of thermal and fast reactors. This would reduce the fraction of fast reactors required for as long as the mix was continued. It also provides "buffer" recycling capability, where changes in transuranic supply from LWRs could be accommodated by changing the amount of recycling in thermal reactors, leaving the fast reactor portion of the fleet unaffected.

For example, at fast reactor TRU conversion ratio[2] of 0.25, the static equilibrium fraction of fast reactors would drop from 27% without thermal recycling to 19% with thermal recycling.

Backup recycling – Recycling in thermal reactors if economic or acceptance problems develop with fast reactor recycling. The separation plant processing used LWR fuel is assumed to start before fast reactors to provide the fast reactors with fuel.[3] Thus, if economic or acceptance problems develop later with the fast reactor component of the program, the choice is among terminating the separation plant, thus incurring costs; accept the accumulation of separated transuranic material; or recycle the material in thermal reactors. Backup recycling with either IMF or MOX could be continued for as long as needed, resuming recycle in fast reactors when possible.

Pure thermal recycling – Recycling in thermal reactors with no intention to use fast reactors. One recycle pass in thermal reactors does not meet advanced fuel cycle objectives; many recycle passes are required.

Recycling in thermal reactors is sustainable provided two constraints are addressed. First, thermal reactors preferentially consume fissile isotopes versus fertile; thus, continued recycling requires a continuing source of fissile material. The most practical source of new fissile material is enriched uranium or new used LWR fuel; either approach reduces the benefit of recycling the original material because of dilution with new material.

The other constraint is that thermal reactor physics (Appendix A) inherently promotes faster accumulation of higher transuranic elements. The higher transuranic elements are much more prone (orders of magnitude) to emit neutrons. The greater shift to higher transuranic elements in thermal reactors than in fast reactors can therefore lead to much higher neutron emissions. The thermal-to-fast penalty depends on many factors, but may be several orders of magnitude. Five approaches to this challenge have been proposed, as follows:

- Only recycle in fast reactors, which is the GNEP approach.
- Recycle the higher transuranic elements (curium and above) in fast reactors and the lower transuranic elements in thermal reactors.

[2] The "conversion ratio" is used throughout this report to mean the TRU conversion ratio (CR), the production rate of transuranics divided by their destruction rate. CR <1 is a TRU consumer or burner; CR >1 is a TRU breeder.
[3] An alternative method to start the first fast reactors is to use excess weapons plutonium.

- Dispose of the curium (and above). This limits the equilibrium reduction in heat load to the repository to ~10x or less after many recycles, compared to ~100x for pure fast systems.

- Store the curium (and above) to let key isotopes delay.[Collins2004, Collins2007] Storage for several decades allows Cm244 (18.1 year halflife), Cf250 (13.1 year), and Cf252 (2.638 year) to substantially decay. These isotopes are responsible for 90% to 99% of the neutron emission when all transuranics are recycled in thermal reactors. While requiring relatively expensive facilities, such storage approaches appear capable of reducing the neutron emission for equilibrium fuel compositions by a few orders of magnitude.

- Accept the penalties of accumulating higher transuranic elements in thermal reactors. Compared to only recycling Pu, repeated recycle of all transuranics in either thermal or fast reactors results in higher heat, gamma, and neutron emission. In particular, in thermal reactors, the penalty for recycling all transuranics is 10,000x to 100,000x higher neutron emission. These high-energy neutrons are difficult to shield. The issues associated with neutron-emitting fuels have been identified.[Briggs2002, NEA2005] Additional analyses is recommended before serious consideration of such an approach.

It is important to note that some of the options above require separations processes that haven't yet been demonstrated successfully.

As with other recent U.S. advanced fuel studies, this report uses heat load as a major metric to assess benefit to the geologic repository.[Wigeland2004, Wigeland2006a] This factor is the increase in the amount of residual high-level waste that can be sent to the repository, assuming that repository capacity is based on temperature constraints (discussed in section 2) rather than current statutory limits, which are more restrictive. (The calculations are always normalized to LWR once-through at 50 MW-year/kg-HM burnup and by the amount of energy produced from the fuel – assuming that the material is then disposed.)

Four clarifications are important to this report. First, these factors are defined for a specific number of recycle passes assuming that the material is then disposed. The actual heat impact to the repository does not happen, of course, until the material is actually sent to the repository, which does not occur as long as recycle is sustained – hence the importance throughout this report given to sustainability of recycle. The exception is any materials deliberately sent to the repository each recycle such as processing losses (~0.1%) and (in some options) specified transuranics.

Second, for some concepts, there are blending effects. Thermal reactors require blending in an amount of new fissile material to sustain recycles, this is done in varying ways in different concepts. The net effect is to adjust the "amount of energy generated" term, which always lowers that improvement factor for that recycle.

Third, one can estimate an equilibrium improvement factor. These are calculated on the basis of the equilibrium fuel cycle composition – fuel is discharged, transuranic elements separated,

mixed with any new material, fabricated into new fuel, inserted into the reactor. The only material going to the repository is the processing losses.

Fourth, to achieve high improvement factors, more than recycle and consumption of transuranic elements is required. In particular, cesium-137 and strontium-90 must be removed and managed so that their heat is segregated from the residual long-term waste sent to the repository. The amount of cesium-137 and strontium-90 are only weak functions of which isotopes fission; so this component to the calculation does not vary significantly among the options considered here. High improvement factors are impossible without dealing with both transuranics and Cs-Sr.

The equilibrium heat load improvement factor for a geologic repository can be ~100x if all transuranics are recycled and no blending of additional transuranic material is done each cycle. This combination can only occur with fast reactors in the system. All thermal systems require blending of additional transuranic material and thus cannot reach as high performance. If the Cm/Bk/Cf accumulation problem is resolved by disposal of these elements, the combination of such disposal and blending limits equilibrium performance to ~10x or less (higher for IMF than MOX). If Cm/Bk/Cf is not disposed, the equilibrium performance is intermediate between ~10x and ~100x.

Of all options studied, repository benefits may accrue the fastest (as measured by the number of recycle passes) by one to three IMF cycles followed by fast reactors; this appears faster than fast reactors alone and more sustainable than thermal recycle alone. If too many thermal cycles are done, accumulation of high transuranic isotopes degrades performance.

General results for thermal recycle

The approach of using only fast reactors to recycle separated transuranics requires coordination among the construction of capability for chemical separation of used LWR fuel, fabrication of new recycled fuel, and fast reactors. Adding some thermal recycling to this approach is a way to provide more latitude in the timing of when new reactors come on line.

Thermal recycle does not eliminate the eventual need for fast reactors, a need driven by achieving highest repository benefits and eventually extending uranium supplies by shifting fast reactors to the breeder mode. The improvement in uranium ore utilization relative to the current once-through fuel cycle is limited to 20% improvement in thermal or low conversion fast reactors, whereas fast reactors in the breeder configuration can achieve a factor of one hundred improvement.

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1. INTRODUCTION

1.1 Purpose

This report summarizes the potential benefits of recycling used Light Water Reactor (LWR) nuclear fuel in thermal reactors, either back into LWRs themselves or into gas-cooled Very High Temperature Reactors (VHTRs). Because most information and most interest in thermal recycling uses LWRs to recycle, rather than VHTRs, the report focuses on LWRs.

This report is not intended to select a particular approach to thermal recycling. Rather, it is a survey of how recycling in thermal reactors could be used with fast reactors to recycle and consume transuranic elements (TRU) from used LWR fuel. The potential benefits of recycling in thermal reactors are assessed against the goals and objectives of the Advanced Fuel Cycle Initiative (AFCI) and now the Global Nuclear Energy Partnership (GNEP).

The main goals of advanced fuel cycles [DOE2006, DOE2007] are to:

- Reduce the number of geologic repositories required this century to one.
- Recycle used nuclear fuel to minimize waste and control weapons-usable inventories.
- Reuse valuable parts of used nuclear fuel to maximize the energy derived from uranium ore.

Advanced fuel cycles address a critical national need associated with past, current, and future use of nuclear energy – to increase the sustainability of nuclear energy. First, the AFCI is developing technologies that should allow more efficient disposition of used fuel and high-level waste, delaying the need for additional geologic repositories into the next century. Second, all advanced fuel cycles would incorporate more proliferation-resistant technologies and designs than employed in current international practice, would reduce the inventory of weapons-usable material by consuming plutonium more quickly, and would reduce the need for uranium enrichment. Third, the AFCI/GNEP investigates fuel cycles that would convert current waste liabilities into energy source assets, ensuring that availability of uranium ore resources does not become a constraint on nuclear energy. While accomplishing these objectives, the AFCI seeks to ensure competitive economics and excellent safety for the entire nuclear fuel cycle.

This report considers how thermal recycling might be useful, when, and why. This requires identifying potential roles for thermal recycling, as opposed to the other two major classes of alternatives – no recycling of any kind (once-through fuel cycle) or recycling only in fast reactors. Basically, thermal reactors operate with relatively low energy neutrons; they are by far the dominant type of reactor that exists today; there are ~440 commercial thermal reactor power plants in operation around the world. Fast reactors operate with relatively high energy neutrons; they are a more advanced approach, which offers the potential for improved fuel cycle performance, they may be deployed relatively soon this century (~2025),[GIF2002] later this century, or not at all.

The major potential roles for recycling in thermal reactors include the following:

1. **Stop-gap –** Recycle once in thermal reactors as a way to initiate recycling while waiting one or two decades for a significant number of fast reactors to be built. The intent thereafter would be to phase out thermal recycling in favor of fast recycling.
2. **Mixed** – Recycle using a symbiotic mix of thermal and fast reactors to recycle used fuel. This is a way to substantially reduce the number of required fast reactors as long as the mix of thermal and fast reactors is used.
3. **Backup** - Recycle in thermal reactors (possibly for several decades) if economic or acceptance problems develop with fast reactor development and deployment. The intent would be to resume recycle in fast reactors when possible.
4. **Pure thermal** - Thermal reactors as the only planned mechanism to recycle used fuel.

The first three roles could be part of the risk mitigation associated with the GNEP approach of using only fast reactors to recycle used nuclear fuel. The last role was considered in the AFCI, but is not part of the GNEP strategy.

Hypothetical delays in fast reactor deployment are postulated in this report to explore potential benefits of recycling in thermal reactors. Nothing in this report is intended to imply that such delays are likely or desirable.

1.2 Scope

Sections 1, 2, and 3 provide the content for assessing fuel cycle benefits. Section 2 of this report explains the goals, objectives, and metrics for assessing fuel cycle benefits. Section 3 describes fuel cycle options. Table 1-1 lists the full range of potential fuel cycle strategies.[DOE2006, DOE2007] This report focuses on the middle columns – recycle in thermal reactors only and sustained recycle with a symbiotic fleet of thermal and fast reactors.

Table 1-1. Potential Fuel Cycle Strategies

Strategy and Variations	Once through	Thermal reactors only (**Pure thermal**)		Symbiotic mix of thermal and fast reactors		Fast reactors only
	Not considered here	Considered in this report				Not considered here
	Fuel burnup can vary from current values to perhaps double	Once	Repeated	Recycle in thermal & fast **(Stop-gap, mixed, backup)**	Recycle in fast only **(GNEP)**	Fast reactors displace thermal reactors
Illustrative technology options that could implement strategy						
Thermal reactors	LWRs or VHTRs or both					None
Fast reactors	None			Sodium cooled		

Section 4 analyzes potential benefits via steady-state or equilibrium analyses. These are relatively straightforward to calculate and to understand. Relative to time-dependent or dynamic

analyses, there are fewer assumptions. So, section 4 is relatively broad in the issues addressed, but less detailed. It helps to narrow the range of issues and range of options to be considered further.

Section 5 analyzes potential benefits via time-dependent or dynamic analyses. This report considers five cases:

- Multiple recycle passes in LWRs using mixed uranium-transuranic oxide (MOX) fuel
- Multiple recycle passes in LWRs using uranium-free inert matrix fuel (IMF)
- One recycle pass in LWRs with MOX, followed by recycle in fast reactors
- One recycle pass in LWRs with IMF, followed by recycle in fast reactors
- No recycle in LWRs; LWRs only provide the source of transuranic material for fast reactors. This is the GNEP approach; it is provided for comparison with the other cases.

The first two are "pure thermal," the next two cases recycles transuranics with a combination of thermal and fast reactors, and the last one is the GNEP approach.

Two technological approaches to recycling transuranic elements in LWRs are considered in this report – MOX and IMF. MOX refers to fuels of mixed oxides of uranium and one or more transuranic elements. Thus, MOX-Pu means a mixture of uranium and plutonium. MOX-TRU means a mixture of uranium and all the transuranic elements relevant to the case being analyzed. IMF means "inert matrix fuel", which is fuel that lacks uranium but includes one or more transuranic elements. For example, IMF-NpPuAm means IMF with neptunium, plutonium, and americium. Eliminating uranium from the fuel means that no new transuranic elements can be created, but it also means that the chemical matrix of the fuel must be based on something other than uranium. This requires finding an alternative matrix material that, like uranium, is sufficiently easy to chemically separate but sufficiently stable to give good fuel performance.

While there is considerable experience for MOX-Pu fuel and limited experience with IMF-Pu, MOX-TRU and IMF-TRU have both been judged to be at the same low level of technology readiness [DOE2006] because both technologies involve fabrication with americium and curium (and differences in the associated fuel performance), which is a substantially different challenge than MOX-Pu or IMF-Pu.

Section 6 summarizes conclusions and lists additional work that could be done to resolve key issues.

The Appendices provide additional background. Appendix A describes the difference between thermal and fast reactors. Appendix B explains which chemical elements should be separated and recycled. Appendix C lists key parameters used in the dynamic analyses.

1.3 Nomenclature

Before going further, it is important to clarify key terminology in this report. The analysis resumes in section 1.4 with a summary of key differences between thermal and fast reactors from the perspective of fuel cycles.

1.3.1 Nomenclature - Fast versus Thermal Reactors

The differences between thermal and fast reactors are a major theme throughout this report. Table 1-2 shows another way to see how the various options are related to each other.

Table 1-2. Fuel Cycle Options including Potential Roles for Recycling in Thermal Reactors

	Only thermal reactors	**Both thermal and fast reactors**	**Only fast reactors**
No recycle in thermal reactor (no role for thermal recycling)	*Once-through fuel cycle, no recycling of any kind*	*Fast reactors consume more transuranic elements than they make ("burner" or "consumer" mode) – thermal reactors supply transuranic material*	*Fast reactors make more transuranic elements than they consume ("breeder" mode) – thermal reactors phased out*
Single recycle pass in thermal reactors	**Pure thermal** - Single pass in thermal reactors	**Stop-gap** - recycling while waiting for fast reactors, e.g., 1 recycle pass in LWR then move to fast reactors. **Mixed** – same as above except continue the symbiotic recycling in a mix of LWRs and fast reactors for as long as desired.	N/A
Multiple recycle passes in thermal reactors	**Pure thermal** - Repeated passes in thermal reactors	**Backup** – Go back to thermal reactor recycling for several decades if economic or acceptance problems develop with fast reactors. Resume fast reactors when possible.	N/A

1.3.2 Nomenclature - How Fuel can be Organized within a Reactor

This subsection clarifies the terminology describing how fuel can be organized within a reactor.

The internal active part of a nuclear reactor is called the **core**. A core is comprised of many "fuel assemblies." A **fuel assembly** is a group of fuel pins or pellets that is added or removed from the core as a single unit during re-fueling.

The core can be either **homogenous** or **heterogeneous**. A homogenous core uses the same fuel composition throughout, that is, all the fuel assemblies in the core are the same. A heterogeneous core uses different fuel assemblies in different regions.

The best example of a heterogeneous core involves one type of fuel assembly in the inner core and another type surrounding the inner core, sometimes called a "blanket." In fast breeder reactors, for example, the highest energy neutrons are in the inner core, which is used to provide most of the fissions with low losses from neutron capture (Appendix A). Neutrons leaving the inner core enter the blanket and are captured in uranium-238 thereby breeding more transuranic fuel.

A fuel assembly can also be either **homogenous** or **heterogeneous**. A homogenous assembly uses the same fuel composition throughout. A heterogeneous assembly uses two or more fuel compositions within the fuel assembly and/or uses a mix of fuel and target pins. "**Fuel**" means a net source of neutrons that keep the reactor going. "**Target**" refers to a pin, pellet, etc. that is a net sink of neutrons.

To show how these concepts can be combined, consider the following options for recycling transuranic elements in thermal reactors. Even if the fuel composition averaged over a reactor core is the same, the options below can change fuel cycle performance and cost.

Homogenous

- Homogenous fuel assemblies with a single composition of a mixed uranium-transuranic oxide, or "Mixed Oxide" (MOX). The mixed oxide can be uranium-plutonium, or uranium-plutonium-neptunium, etc. The U/Pu, U/NpPu, etc. composition is kept the same. By definition, mixed oxide fuels always have uranium as a key ingredient. The uranium can be recycled from used LWR fuel (once burned), depleted, natural, or enriched in various schemes.
- Homogenous fuel assemblies with a single composition of uranium-free fuel often called inert-matrix fuel (IMF). The active ingredient (fuel) is one or more transuranic elements. Passive ingredients that keep the fuel together (inert matrix) are materials that are too light in atomic number to fission so that they do not produce neutrons. Good passive ingredients also capture as few neutrons as possible.

Heterogeneous

- Heterogeneous fuel assemblies with a mix of enriched uranium oxide fuel (for example ¾ of the pins) and uranium-free IMF (for example ¼ of the pins).
- Heterogeneous fuel assemblies with a three-way mix of enriched uranium oxide fuel (for example ¾ of the pins), uranium-free fuel (for example ¼ of the pin) as a way to consume plutonium, and a few targets of americium. The americium targets could be oxide, metal, etc.
- Many other combinations are possible.

The homogeneous cases only require one type of fuel to be produced. If the fuel only contains enriched uranium (i.e. current LWR fresh fuel), it can be made hands-on. If the fuel only contains plutonium but not higher transuranic elements, it generally can be made in gloveboxes, (at least for the first recycle pass) which is somewhat more expensive than hands-on. If the fuel (or target) contains americium or curium, their high radiation field means that it must be made with fully remote equipment, which is significantly more expensive.

The heterogeneous cases are partly motivated by reducing the potential remote fabrication penalty associated with recycling americium or curium – but at the cost of requiring multiple types of fuels to be developed and produced, and more chemical separation steps. The last of the cases listed above, for example, would have ~75% of the fuel pins made hands-on, ~23% made in gloveboxes, and less than 2% made remotely (the americium targets). This requires three fuel/target types, and more chemical separation steps than keeping all the transuranic elements together. The separation of Am from Cm (and above) has proven to be difficult.

1.3.3 Nomenclature - Blending Strategies

One additional complication needs to be clarified. After the first recycle pass, the remaining transuranic material can be used **directly** in the next recycle pass or **blended** with fresh transuranics. All of the fast reactor analyses in this report use the direct approach; this is also used in a few of the thermal reactor cases. Most of the thermal reactor cases analyzed in this report use the blended approach to keep the blended material capable of sustaining the fission reaction. Without blending, the remaining TRU becomes unusable in thermal reactors after one or two thermal recycles.

1.3.4 Nomenclature – Conversion Ratio

The "conversion ratio" is used throughout this report to mean the TRU conversion ratio, the production rate of transuranics divided by their destruction rate. CR <1 is a TRU consumer or burner; CR >1 is a TRU breeder.

1.3.5 Nomenclature - Equilibrium

This report considers both "static" and "dynamic" equilibrium. Static equilibrium refers to relatively simple analyses where time lags have little importance; in particular, the impacts of growth of nuclear power are ignored as are the effects of retirement of the current reactors Thus, the system is analyzed as if it remains at 100 GWe, the same capacity as in the U.S. today. A key static equilibrium result is that at TRU conversion ratio of 0.25, the fraction of fast reactors in a mixed recycle scenario must be 27% of the fleet.

Dynamic equilibrium considers a wide range of time dependent effects, including the growth of nuclear power. Calculations in this report use 2.25%/year nuclear growth with the first new nuclear power plants assumed to be on line in 2015. The U.S. nuclear power fleet exceeds 700 GWe by 2100. Dynamic analyses are presented in section 5. In some cases, a relatively stable equilibrium is established. In other cases, the system continues to evolve significantly. A key dynamic equilibrium result is that at TRU conversion ratio of 0.25 and the various time lags assumed in this report, the fraction of fast reactors in a mixed recycle scenario starts at zero and reaches a dynamic equilibrium around 18% of the fleet in the second half of this century. This can only occur after the current LWR fleet retires, once fast reactors are assumed to be built if the TRU supply is adequate, the rate of separation capacity coming on line follows the growth in nuclear power.

1.4 Importance of Fast versus Thermal Reactors for Fuel Cycles

As additional background for the reader, Table 1-3 summarizes key differences between thermal and fast reactors.

Table 1-3. Comparison of Thermal and Fast Reactors

	Thermal reactors	Fast reactors
Fraction of current world-wide operating reactors	>99%	<1%
Maximum fraction of theoretical energy content in uranium ore that can be released	~1%	~100%
Heavy elements providing net source of neutrons (hence these are potential fuels, see section 1.4)	U, Pu, and Cm	U and all the transuranics (Np, Pu, Am, Cm)
Heavy elements providing a net sink of neutrons (these are potential targets)	Np and Am	None
Fraction of natural uranium readily usable as fuel	Uranium-235 (only 0.7% of uranium ore)[4]	Uranium-235 and 238 (100% of uranium ore)
Fraction of uranium and transuranic mass that can be readily used as fuel	Few percent	All
Fraction of uranium and transuranic isotopes that can be readily used as fuel	< half (only the "fissile" isotopes such as U-235 and Pu-239)	All (both fissile and fertile isotopes)
Average energy of neutrons	Low	High
Restrictions on use of materials	Can be designed with a wide variety of non-fuel materials, including water as a coolant	Use of some materials, such as water, is restricted in fast reactors because they moderate neutrons

In this report, all fast reactor options (except the breeder) are assumed to have a TRU conversion ratio (CR) of 0.25, that is, for every 4 TRU atoms consumed in the fast reactor, one new TRU atom is created. In GNEP, conversion ratios of 0.25 to 0.75 are under consideration. We use a single CR case to simplify the comparison and because only CR=0.25 data were available for all the relevant cases described in section 3.

[4] Fertile uranium-238 will capture a neutron, becoming fissile plutonium-239, which also fissions readily. However, many non-fuel materials will also capture (and waste) neutrons.

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2. GOALS, OBJECTIVES, AND METRICS

This section explains the GNEP goals, objectives, requirements, drivers, and quantitative targets as the basis for technology decisions and analyses in later sections.

2.1 Goals and Objectives

The goals of the GNEP program are to:

- "Reduce the current and future burden related to geologic disposal of spent nuclear fuel in terms of waste volume, heat load, radiotoxicity, and number of repositories needed.
- Recover the energy value contained in spent nuclear fuel for future energy production needs.
- Reduce the proliferation risk associated with the use of nuclear energy globally."[GNEP2006a]

These goals can only be realized by developing a closed fuel cycle and implementing a multi-pronged approach to development of advanced nuclear energy systems. This translates into the following objectives of GNEP:[GNEP2006b]

- "Expand domestic use of nuclear power
- Demonstrate more proliferation-resistant recycling
- Minimize nuclear waste
- Develop advanced burner reactors
- Establish reliable fuel cycle services
- Demonstrate small-scale reactors
- Develop enhanced nuclear safeguards."

2.2 Deployment System Requirements

Per the GNEP Technical Development Plan,[GNEP2006b] various considerations result in seven technical requirements that must be met by the GNEP deployment system of technologies:

1. "The system must result in a significant improvement in repository utilization, preferably avoiding the need for a second geologic repository this century.
2. The system must optimize waste management including minimizing waste that need to be handled or stored, and producing only solid waste with robust waste forms.
3. The system must make available the energy value of separated materials for future use
4. The system must reduce proliferation risk.
5. The system must be deployable in a timeframe so as to reassert U.S. leadership, and influence fuel cycle development worldwide (20 years).
6. The system must remain as economical as possible.
7. The system must be environmentally sound."

With one exception, these requirements are not different than the earlier AFCI program. The exception is the 20-year requirement to be ready for deployment.

2.3 Metrics

More specific targets are required, derived from the above goals, objectives, requirements,[DOE2005, GNEP2006a, GNEP2006b] and various analyses.[Piet2006, Wigeland2005, Wigeland2006a, Wigeland2006b, Collins2004, Collins2007] Fundamentally, the requirements and goals require that we enable sustained separation, recycle, and transmutation of TRU. The GNEP Technology Development Plan [GNEP2006b] contains more description of the various types of analyses that are being performed. Table 2-1 lists targets considered in assessments of how well options meet GNEP program requirements and thus provide benefits.

Table 2-1. Targets for Assessment of How Deployment Meets GNEP Program Requirements

Goals and Requirements	Targets	Comment
"Reduce the current and future burden related to geologic disposal of spent nuclear fuel in terms of waste volume, heat load, radiotoxicity, and number of repositories needed."[GNEP2006a]	"In the short-term,[5] develop and demonstrate fuel cycle technologies and facilities that remove more than 99.5 percent of transuranics from waste destined for geologic disposal." [DOE2005]	If recycle is sustained, these targets allow deferment of a second geologic repository to the next century, which is ensured by a long-term heat to repository reduction of 50x. These targets require demonstration of the technology to separate plutonium, americium, curium, cesium, and strontium. The transuranics are consumed; Cs and Sr are segregated for decay storage. Also, technetium and iodine must be separated from wastes that are not destined for geologic disposal.
	"In the short-term, improve management of the primary heat producing fission products in spent fuel (cesium and strontium) to reduce geologic repository impacts."[DOE2005]	
	"In the intermediate- and long-terms, reduce the long-lived radiation dose sources by a factor of 10 and radiotoxicity by a factor of 100, simplifying the design of a waste isolation system."[DOE2005]	Recovery of neptunium, plutonium, and americium reduces radiotoxicity by 100x at 1,000 yrs after reactor discharge so waste is less toxic than uranium ore at long times. It also reduces long-term hypothetical offsite dose from material by 10-50x.
"Recover the energy value contained in spent nuclear fuel for future energy production needs." – "The system must make available the energy value of separated materials for future use." [GNEP2006a]	"In the short-term, develop the technologies needed to extend nuclear fuel supplies by up to 15 percent by recycling the fissile material in spent nuclear fuel."[DOE2005]	This requires technologies that separate U and all of the transuranic elements for later use
	"In the long-term, extend nuclear fuel resources more than 50-fold by recycling uranium in spent fuel and depleted uranium, thereby converting current wastes into energy assets." [DOE2005]	This requires sustainable recycle with fast reactors in the breeder configuration.

[5] For purposes of the targets in the 2005 report, "short-term" refers to the period through 2025, when the program recommends the need for a commercially-deployed spent fuel treatment facility. "Intermediate-term" refers to the period from 2025 until the commercial availability of fast spectrum reactors. "Long-term" refers to the time after several of these fast reactors have been built.

Goals and Requirements	Targets	Comment
"Reduce the proliferation risk associated with the use of nuclear energy globally." - The system must reduce proliferation risk." [GNEP2006a]	"In the short-term, develop fuel cycle technologies that enhance the use of intrinsic[6] proliferation barriers." [DOE2005]	Inclusion of one or more additional transuranic elements with plutonium works toward this goal.
	"In the short-term, demonstrate the capability to eliminate more than 99.5 percent of transuranic weapons-usable materials from waste streams destined for direct disposal by destroying these materials through recycling." [DOE2005]	This requires separation and recovery of the transuranic elements.
	"In the long-term, stabilize the inventory of weapons-usable material in storage by consuming it for sustained energy production." [DOE2005]	
The system must be deployable in a timeframe so as to reassert U.S. leadership, and influence fuel cycle development worldwide. [GNEP2006a]	Demonstrate technologies within 20 years, enabling deployment thereafter if results are favorable.[GNEP2006b]	
The system must remain as economical as possible. [GNEP2006a]	Include the entire fuel cycle in the assessment, balancing costs of separation, fabrication, reactors, waste management, etc.[DOE2005, etc.]	At the system level, considerations such as storage within the system and throughput (mass flows) are important.
The system must be environmentally sound. [GNEP2006a]	Demonstrate safe operation, meet all regulations[DOE2005, etc.]	Unlike existing technologies, the AFCI chemical separation technology UREX+ is designed to avoid production of any liquid wastes. The AFCI chemical separation technology pyroprocessing working fluids have high melting points and would freeze outside of their processing equipment; they also avoid production of any liquid wastes. Waste forms must be stable.

Perhaps the most important quantitative targets are the following (relative to once-through):

- Reduce long-term heat (LTH) commitment to a geologic repository by 100x.

[6] "Intrinsic" proliferation resistance features, as defined in the International Atomic Energy Agency (IAEA) Department of Safeguards STR-332, *Proliferation Resistance Fundamentals for Future Nuclear Energy Systems*, include (but are not limited to) technical features that: Reduce the attractiveness for nuclear weapons programs of nuclear material during production, use, transport, storage and disposal; Prevent or inhibit the diversion of nuclear material; Prevent or inhibit the undeclared production of direct-use material; and Facilitate verification, including continuity of knowledge.

- Reduce long-term radiotoxicity (LTR) by 100x, thereby reducing the radiotoxicity of residual high level waste (HLW)/repository waste to that of uranium ore in less than 1,000 years instead of less than 1,000,000 years for once-through (Appendix B).
- Reduce long-term hypothetical offsite dose (LTD) from a geologic repository by 10x.
- Improve uranium ore utilization by 1.15x in the short term and 50x in the long term.
- Demonstrate technologies within 20 years.

As with other recent U.S. advanced fuel studies, this report uses heat load as a major metric to assess benefit to the geologic repository.[Wigeland2004, Wigeland2006a] This factor is the increase in the amount of residual high-level waste that can be sent to the repository, assuming that repository capacity is based on temperature constraints rather than current statutory limits. The calculations are always normalized to LWR once-through at 50 MW-year/kg-HM burnup and by the amount of energy produced from the fuel – assuming that the material is then disposed. The objective is to achieve an improvement of ~100x.[DOE2005, DOE2006, DOE2007]

Four clarifications are important to this report. First, these factors are defined for a specific number of recycle passes assuming that the material is then disposed. The actual heat impact to the repository does not happen, of course, until the material is actually sent to the repository, which does not happen if recycle is sustained – hence the importance throughout this report given to sustainability of recycle. The exception is any materials deliberately sent to the repository each recycle such as assumed processing losses (~0.1%) and (in some options) specified transuranics.

Second, for some concepts, there are blending effects. Recognize that transuranics after cycle-N have literally been through that reactor N times. (The actual physical fuel in reactors will generally have a mixture of transuranic material at a mix of recycle passes.) As explained elsewhere in the report, fast reactors can continue to recycle the original transuranic material indefinitely, each time less mass remains after being used in the reactor. Thermal reactors, however, require blending in an amount of new fissile material to sustain recycles, this is done in varying ways in different concepts. The net effect is to adjust the "amount of energy generated" term, which always lowers that improvement factor for that recycle.

Third, one can estimate an equilibrium improvement factor. These are calculated on the basis of the equilibrium fuel cycle composition – fuel is discharged, transuranic elements separated, mixed with any new material, fabricated into new fuel, inserted into the reactor. The only material going to the repository is the assumed processing losses.

Fourth, to achieve high improvement factors, more than recycle and consumption of transuranic elements is required. In particular, cesium-137 and strontium-90 must be removed and managed so that their heat is segregated from the residual long-term waste sent to the repository. The amount of cesium-137 and strontium-90 are only weak functions of which isotopes fission; so this component to the calculation does not vary significantly among the options considered here.

3. OPTIONS

3.1 Fuel Cycle Strategies

Advanced fuel cycle planning focuses on a full range of options, grouped into the following four possible strategies as defined in annual program comparison reports.[DOE2006, DOE2007] In this context, a strategy is a general approach to fuel management that encompasses a range of options with similar basic characteristics. A strategy identifies which materials are recycled (if any), the type of nuclear power plant, the type of used fuel processing technology, and which materials go to geologic disposal. A complete fuel cycle specification must address in some fashion uranium, transuranic elements, short-lived fission products such as cesium and strontium, and long-lived fission products such as iodine and technetium (see Appendix B).

The current U.S. strategy is **once-through**: After one pass through a reactor, the components of used fuel are kept together and sent to a geologic repository.

- One variation is to assume that the burnup (the amount of energy extracted per mass of input fuel) stays about constant at 50 MW-thermal-day/kg-fuel.
- The other variation considered is to assume burnup doubles to 100 MW-thermal-day/kg-fuel. This would require higher uranium enrichment and fuel technology developments. It would cut the mass of future used fuel in half for the same total energy generation.

The second strategy is recycling in **thermal reactors only**. Uranium in used fuel and depleted uranium would be disposed as low-level waste. (Some uranium could be re-enriched and made into new fuel.) Transuranic elements would be recycled one or more times. Depending on the recycle details, it is possible to have essentially no transuranic elements in the HLW/repository waste stream, only processing losses. Long-lived fission products would also go to geologic disposal. Targeted short-lived fission products would be first stored while they decay and become less radioactive and ultimately disposed of as low-level waste. This strategy uses existing or future thermal reactors.

- One variation is to recycle only once.
- The other variation is to recycle repeatedly. Two such cases are included in section 5 – MOX and IMF.

The third strategy is sustained recycle with a **symbiotic mix of thermal and fast reactors**, recycling transuranic elements from used fuel repeatedly until destroyed. The introduction of fast reactors makes this strategy sustainable from the repository standpoint; the accumulation of transuranic elements during repeated recycle passes is controlled and limited by fast reactors serving as transuranic element burners. Essentially no transuranic elements would go to geologic disposal, except as processing losses. Uranium and fission products would be disposed of as with thermal recycling, except a small fraction of the uranium would be converted to energy. This strategy requires a significant fraction of future nuclear power plants to be fast reactors.

- One variation is that recycled transuranic material is used in only fast reactors; this is the GNEP approach.
- Another variation is that recycled transuranic material is recycled in both thermal and fast reactors. This approach is envisioned by some countries that currently do limited recycle

in thermal reactors. If fast reactors prove more expensive than LWRs, this approach could also be used to lower the fraction of required fast reactors. Two such cases are included in section 5 – MOX and IMF.

The fourth strategy is sustained recycle with **fast reactors only**, recycling both uranium and transuranic elements repeatedly until all energy is extracted. Phasing out thermal reactors in favor of fast reactors means that all types of uranium ultimately serve as fuel; thus, this strategy is sustainable both in terms of repository constraints and in terms of uranium ore resources. The TRU conversion ratio of the fast reactors must be raised over 1, i.e., the fast reactor would be in the breeder configuration. Essentially no uranium or transuranic elements would be wasted, only processing losses. As with other recycle strategies, long-lived fission products would tend to go to permanent disposal; short-lived fission products would be stored and ultimately disposed of as low-level waste after sufficient decay.

3.2 Options Analyzed in this Report

Table 3-1 lists the options in this report for purposes of clarifying potential benefits from recycle in thermal reactors. The list is not exhaustive, e.g., the analysis did not include the case of 2 passes in thermal reactor followed by fast reactors. There are many past studies that explore parameter variations; the cases here are representative of a wide range of possibilities. The purpose of this report is not to identify one or more specific thermal recycle cases, but instead to identify what thermal recycle can and cannot do, and why.

Table 3-1. Options Analyzed in this Report

Strategy	Cases analyzed in Section 4, steady-state or equilibrium analyses	Case also considered in section 5, time-dependent or dynamic analyses
Once-through	Standard burnup in LWRs, 50 MW-day/kg	
	Double burnup in LWRs, 100 MW-day/kg	
Thermal reactors only	1-pass of MOX in LWR	
	1-pass of uranium free IMF in LWR	
	1-pass of uranium free fuel in VHTR (so-called deep burn)	
	Multiple passes with MOX in LWR	**X**
	Multiple passes with IMF in LWRs	**X**
Symbiotic mix of thermal and fast reactor reactors	1-pass MOX in LWR followed by fast reactors	**X**
	1-pass IMF in LWR followed by fast reactors	**X**
	UOX from LWR used in fast reactors, that is, LWRs provide a continuing source of transuranic material, which is consumed in fast reactors (fast reactors in burner mode)	**X**
Fast reactors only	Fast reactor in breeder mode	

Likewise, only one set of parameters was analyzed for each case. For example, when there is 1 recycle pass in thermal reactors followed by fast reactors, all analyses here include a single 5-year decay time between thermal and fast.

3.3 Illustrative Technologies Used in this Assessment

The purpose of this report is not to select technologies. Other reports have compared technologies.[DOE2006, DOE2007] Therefore, unless stated otherwise the analyses in this report use the most common illustrative technologies, as listed in Table 3-2.

Table 3-2. Fuel Cycle Strategies

Strategy and Variations	**Once through**		**Thermal reactors only**		**Symbiotic mix of thermal and fast reactors**		**Fast reactors only**
	Current burnup	Doubled burnup	**Once**	**Repeated**	**Recycle in thermal & fast**	**Recycle in fast only (GNEP)**	
Illustrative technology options that could implement strategy							
Thermal reactors	LWRs or VHTRs						None
Fast reactors	None				Sodium cooled		
Thermal reactor fuels using enriched uranium	Uranium oxide (oxycarbide for VHTRs)						None
Thermal reactor fuels using recycled TRU	None		MOX or IMF with Np, Pu, Am; Cm (and above) is discarded to reduce accumulation of high neutron emitting isotopes (oxycarbides for VHTRs)		MOX or IMF with Np,Pu; Am and Cm (and above) are stored until used in fast reactors, to reduce accumulation of radiation field isotopes (oxycarbides for VHTRs)	None	
Fast reactor fuels using recycled TRU	None				TRU metal (Np, Pu, Am, Cm, Bk, Cf)		
Separation technologies	None		UREX+		UREX+ for oxide fuels; pyroprocessing for metal fuels		

The disposition of transuranic elements is important, see Appendices A and B. So are key groups of fission products.

- Technetium-99 and iodine-129 (Tc-I) are long-lived fission products (0.2 and 16-million year halflives), which generate little heat but are long-term environmental stewardship burdens. UREX+ separates these for separate long-term management; transmutation in reactors is also a theoretical possibility.[Salvatores1998, Yang2004]
- Cesium-137 and strontium-90 (Cs-Sr) are intermediate-lived fission products (~30-yr halflives), with high generation of heat and radiotoxicity. UREX+ separates these elements for separate decay storage (few hundred years) to simplify the management of longer-lived hazards by removing the intermediate heat problem.
- The lanthanides or "rare earths" are short-lived fission products (halflives generally no more than a few years), with very high generation of heat and radiotoxicity for a few years. In some variations of UREX+, the lanthanides are kept with transuranic products

to make unauthorized use of the transuranics more difficult without additional chemical separations.

Table 3-3 lists the variations of the UREX+ suite of technologies. The range of options is an important source of flexibility in adjusting and improving fuel cycle management.

Table 3-3. Variations of the Uranium Extraction plus (UREX+) Suite of Technologies

Process	Products common to all processes	Additional products				
		1	2	3	4	Purpose
UREX+1	Uranium and cesium-strontium at purity sufficient for near-surface disposal. Technetium and iodine for permanent disposal. Disposal of LWR fuel cladding to be determined.	TRU+ lanthanides	All other fission products			Recover TRU with lanthanides inhibiting use of the TRU until need arises
UREX+1a		TRU	All fission products			Recover TRU for near-term recycle
UREX+2		Np+Pu	Am+Cm+ lanthanides	All other fission products		Near-term recycle of NpPu, hold AmCm until need arises or dispose of the AmCm
UREX+3		Np+Pu	Am+Cm	All fission products		Near-term recycle of NpPu and AmCm
UREX+4		Np+Pu	Am	Cm	All fission products	Near-term recycle of NpPu, Am, and either storage or recycle of Cm
The small amounts of Bk and Cf are assumed to follow Cm.						

When only recycle in thermal reactors is contemplated, the most likely approach achieving AFCI objectives is to recycle neptunium, plutonium, and americium (NpPuAm). Discarding curium (whether by separation or waiting for most Cm244 to decay) reduces the accumulation of neutron-emitting higher transuranic isotopes such as Cm244, Cm248, Cm250, and Cf252 while still allowing significant waste management benefits. Recycling NpPuAm while discarding or storing curium requires a relatively high number of chemical separations, e.g., UREX+4 in Table 3-3. Storage of curium would entail its own difficulties.

For cases with only one thermal recycle, in addition to recycle of NpPuAm, this report also includes variants where all four TRU are recycled (NpPuAmCm), or only two (NpPu). It is against U.S. policy to separate plutonium alone.[NEP2001]

For cases where a mix of thermal and fast reactor recycling is contemplated, this report focuses on recycle of plutonium and neptunium in thermal reactors, using the UREX+3 variant. The americium, curium, and unburned residual transuranic material from the thermal reactor are sent to a fast reactor.

When only recycle in fast reactors is contemplated, the most likely approach achieving AFCI objectives is to recycle all the transuranic elements, corresponding to the UREX+1a variant. The accumulation of higher transuranic isotopes is not as much an issue in fast reactors and so recycle of curium is does not cause major problems – there is less heat load to the repository (from the curium) and there are fewer chemical separations required.

The spectrum of possible options is yet broader; the reader is reminded that the purpose of this report is not to identify specific thermal recycling options.

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4. STEADY-STATE OR STATIC EQUILIBRIUM ANALYSES

Section 4 analyzes potential benefits via steady-state or equilibrium analyses. These are relatively straightforward to calculate and to understand. Relative to time-dependent or dynamic analyses, there are fewer assumptions. So, this section is relatively broad in the issues and cases addressed, but less detailed. It helps to narrow the range of issues and range of options to be considered further in section 5. This section (as opposed to section 5) contains the only analyses for the following cases:

- Once-through – only included for comparison
- 1 recycle pass in either LWR or VHTR – because analyses indicate that such cases do not meet objectives described in section 2.
- Breeder fast reactors – because uranium supply is not considered a near-term constraint.[DOE2005]

Also, the only economic analyses to date are steady-state and are contained in this section.

This section starts with analyses of cases using only a single recycle pass in thermal reactors; these are shown inadequate relative to the objectives in section 2. The rest of the section addresses the remaining options against the objectives for advanced fuel cycles – waste management, energy recovery, proliferation risk management, economics, and safety. The key issue of heat, gamma, and neutron emission from recycled transuranic material is relevant to both proliferation risk management and economics.

4.1 Single-pass cases

Table 4-1 lists key results for cases with a single pass in thermal reactors. None of the cases come close to meeting objectives. Single pass cases are not considered further in this report.

Table 4-1. Results for Single-Pass Cases Relative to Once-Through at 50 MW-day/kg burnup

Strategy	Once through [Piet2006]	Single recycle pass in LWR [Piet2006]						Single recycle pass in VHTR [Morris2005]
Fuel	UOX	MOX		IMF				
Subcase	100 MW-day/kg burnup	NpPu	NpPu Am	NpPu	NpPu Am Cm	NpPuAm (blended core)	NpPu, Am target (blended core)	NpPuAm
Reduce long-term heat (LTH) by 50x	1.17	1.07	1.12	1.98	1.82	1.61	1.67	1.8 (Slightly better than analogous IMF case)
Reduce long-term dose (LTD) by 50x	1.12	1.35	1.41	2.09	1.96	1.57	1.63	Should be similar to IMF
Reduce long-term radiotoxicity (LTR) by 100x	1.38	1.12	1.18	2.46	2.39	1.79	1.85	
Improve uranium ore utilization 1.15x in short-term	0.97	1.09	1.07	1.15	1.14	1.13	1.14	
Improve uranium ore utilization 50x in long term								

4.2 Waste Management in Geologic Repositories

Heat is one geologic repository constraint. Therefore, it is important to assess how recycling can reduce the heat to future geologic repositories. See the end of section 2 for important definitions and clarifications regarding the heat-load repository improvement factor discussed in this subsection.

Here, we use a metric of the heat released by residual high-level waste. These metrics help compare approaches, but detailed calculations are needed for trustworthy predictive results. Fast reactors appear to offer the best sustainable performance. Low conversion ratio fuels in thermal reactors (inert matrix fuels) may provide good performance for a few recycles.

Reduction of long-term heat to a geologic repository (taking Yucca Mountain parameters as an example) can increase the loading of residual waste in the repository by factors of ~100x.[Wigeland2006a] That is, the heat impact from the residual post-recycling waste from 100 reactor-years of operation would have comparable heat impact from 1 reactor-year of once-through LWR fuel by (a) recycling and consuming transuranics and (b) segregating for separate heat management intermediate half-life elements cesium and strontium.

The improvement factor increases as the consumption of heat-emitting transuranic elements increases. Advanced fuel cycles also separate uranium for its energy and waste mass reduction and put residual waste (other fission products and transuranic element processing losses) into robust waste forms.

For quick comparison, we use a heat integral. Fifty years is the soonest that repository ventilation may be terminated, ending convective heat removal.[DOE2002] 1500 years is the approximate time of maximum temperature mid way between repository tunnels for the Yucca Mtn design, which requires that temperatures stay below the local boiling water temperature.

The metric was previously calibrated [Piet2006] versus more detailed calculations [Wigeland2006a], see figure 4-1. When the in-between drift temperature limit is the dominant constraint, the metric is an excellent predictor of the heat improvement factor. When other constraints dominate, such as tunnel wall temperature, the metric overpredicts the actual repository capacity improvement factor.

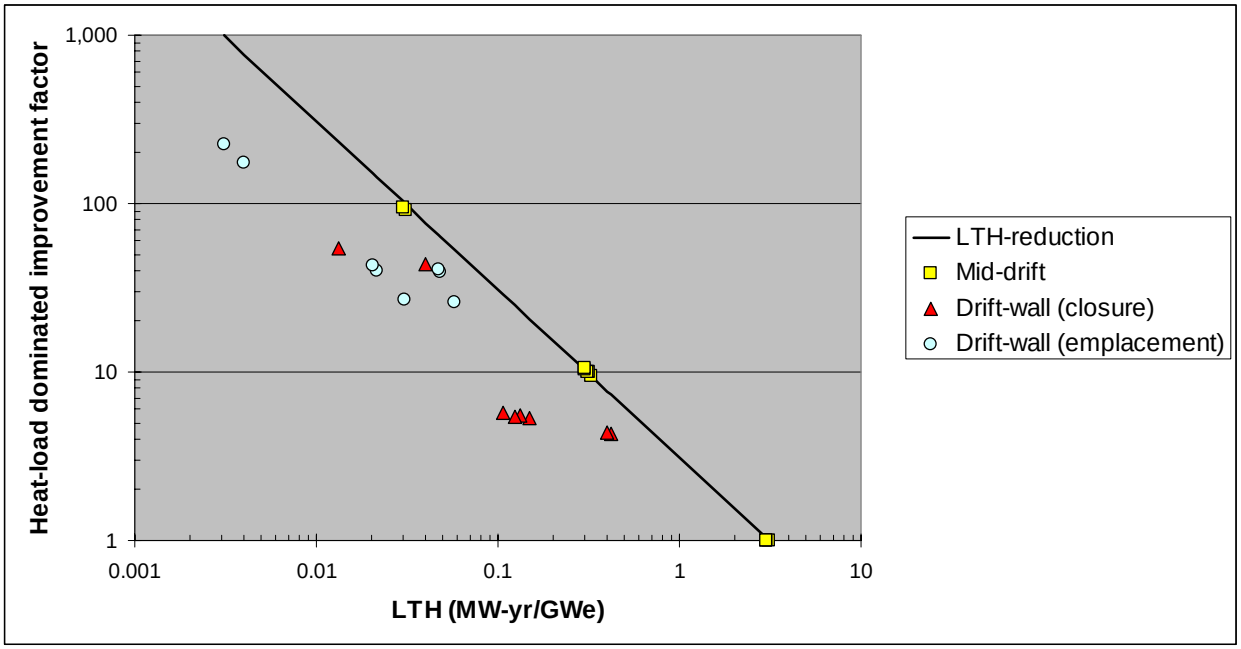

Figure 4-1. Repository capacity heat-load improvement factors versus calculated metric. Heat-load improvement factors are conservatively defined assuming residual material is sent to the repository after the number of recycles indicated.

Figure 4-1 shows that the heat-integral metric matches more detailed calculations when the limiting criterion is the mid-drift temperature, i.e., keeping below the local boiling point of water (96 ºC) in between two tunnels. When the drift-wall temperature constraint (keep wall below 200 ºC) limits, the metric over predicts repository improvement.

Figure 4-2 indicates under what conditions the mid-drift constraint dominates. If the longer-lived isotopes in TRU are well removed and the intermediate-lived Cs-Sr are not, then the drift-

wall temperature constraint tends to dominate. In the following subsections, the cycle-by-cycle cases assume that between 99% and 99.9% of the Cs-Sr is removed, but only a modest fraction of the TRU is consumed. That results in the cycle-by-cycle cases being in the left side of figure 4-2, which is dominated by the mid-drift temperature constraint, which is well matched by the metric used in this study. The only cases in this study that are unlikely to be dominated by the mid-drift temperature constraint are the equilibrium values, but those results have been calculated with more detailed calculations and do not depend on the heat-integral metric.

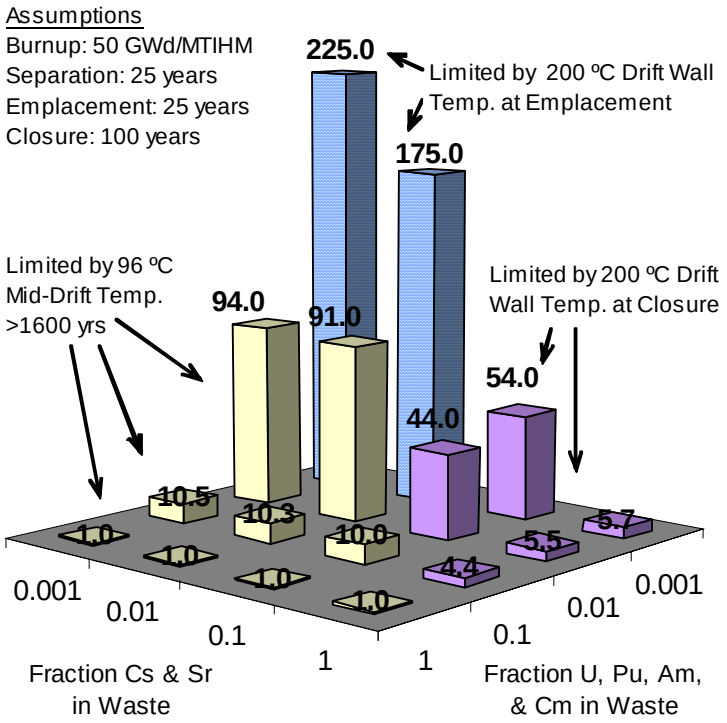

Figure 4-2. Heat-load repository capacity improvement factors [Wigeland2006a]
Heat-load improvement factors are conservatively defined assuming residual material is sent to the repository after the number of recycles indicated.

The AFCI aims to achieve factors of at least 50x to ensure that a second geologic repository will not be needed until the next century.

4.2.1 Thermal Reactors

Thermal reactors readily fission fissile isotopes, but not fertile isotopes. The major consumption pathway for fertile isotopes is neutron capture, which typically transmutes into a fissile isotope at the cost of a neutron.

Fuels can be repeatedly recycled if constraints are met. The fuel must be chemically recyclable, the useful elements recovered and fabricated into new fuel. In thermal reactors, as fissile isotopes are preferentially consumed, repeated recycle requires that they be replaced by blending in new material such as enriched uranium or TRU separated from used UOX. The unblended

approach recycles only the transuranic elements until criticality cannot be maintained. There are other constraints on recycle sustainability not addressed here, e.g., void reactivity coefficients.

NOTE: There are no known calculations for recycle in VHTR that extend more than two cycles.

Figure 4-3 shows results for repeated recycling with MOX-NpPuAm.[Wigeland2004] Recycle of only NpPu would have worse performance because there would be no consumption of Am241. Recycle of all TRU should be similar to NpPuAm. With high CR LWR fuels such as MOX, we have not found cases that achieve factors of 2x even after 7 recycles. Performance is clearly not adequate. For the cases modeled, only 5 years elapse between reactor discharge and recycle as MOX. Performance degrades further with more time lapse because of Pu241 decay into Am241; Pu241 is fissile, Am241 is fertile.

Figure 4-3. Heat improvement factor for LWR-MOX-NpPuAm cases
Heat-load improvement factors are conservatively defined assuming residual material is sent to the repository after the number of recycles indicated.

Figure 4-4 shows results for IMF cases without blending.[Wigeland2004, Hoffman2005a, Hoffman2005b, Piet2006] Without blending, after two recycles, IMF cases recycling Np, Pu, and Am can achieve factors of 2.1x (homogenous core) and 4.2x (heterogeneous core). However, these are dead-end, the material cannot be recycled further without blending in new fissile material.

Figure 4-4. Heat improvement factor for LWR-IMF-NpPuAm without blending
Heat-load improvement factors are conservatively defined assuming residual material is sent to the repository after the number of recycles indicated.

Figure 4-5 shows how the IMF results change with TRU blending to enable additional recycle passes.[Hoffman2005a, Hoffman2005b, Piet2006] With blending, IMF cases recycling Np, Pu, and Am can go beyond two recycles. We have found cases achieving ~3.7x after 10 cycles with a heterogeneous core. In thermal reactors, the rate of improvement decreases as the number of recycles increases because of (a) the required blending of additional TRU to sustain recycling and (b) the accumulated penalty of Cm disposal each recycle. In thermal reactors, Cm disposal avoids accumulation of very high neutron emitting isotopes. Said another way, the results in figure 4-5 would improve with recycling of all TRU together, but at the cost of high accumulation of neutron-emitting Cm244, Cm248, Cm250, and Cf252.

Figure 4-5. Heat improvement factor for LWR-IMF-NpPuAm with blending
Heat-load improvement factors are conservatively defined assuming residual material is sent to the repository after the number of recycles indicated.

The equilibrium IMF-NpPuAm improvement appears to be ~10x, assuming that curium is disposed each cycle.[Hoffman2005a] MOX would appear to be lower. Note that the amount of curium to be disposed increases each cycle; the accumulation of americium isotopes means that more curium is generated each subsequent recycle. It appears that recycling neither high CR (MOX) nor low CR (IMF) fuels in LWRs can achieve the 100x objective, assuming that curium is disposed.

More analysis is required to determine potential benefits if curium is stored for several decades (to reduce the accumulation of neutron-emitting higher transuranic elements) or kept with the recycled transuranics. The heat, gamma, and neutron emission ramifications of the latter are discussed in section 4.4

4.2.2 Fast Reactors

There has been less study of the potential of fast reactor options to achieve high improvement factors. Thus, we have relatively less confidence that the most attractive set of details has been found. We have found cases achieving improvement factors of 3.5x to 4.0x after 5 recycles for fast reactor CR of 1.1 and 0.25,[Stillman2004] see figure 4-6. The behavior shows fundamental differences from thermal recycling.

- The improvement curves do not "turn over" as do the thermal reactor curves.
  - No blending of additional TRU was required to enable multiple recycle passes.

- Curium (and above) is recycled, not disposed. Therefore, there is no heat-load penalty from the accumulation of disposed Cm each recycle.
- The difference between high and low CR is lower. Compare the two fast reactor cases (CR=0.25 vs CR=1.1) versus the thermal reactor cases (IMF with low CR, MOX with high CR). More analyses are in progress to examine fast reactor performance as a function of TRU conversion ratio.

Figure 4-6. Heat improvement factor for fast reactor-NpPuAmCm without blending
Heat-load improvement factors are conservatively defined assuming residual material is sent to the repository after the number of recycles indicated.

At fast reactor CR=0.25, the equilibrium improvement is ~140x (0.2% loss/recycle) to ~56x (0.5% loss/recycle).[Piet2006] It appears that recycling in fast reactors can achieve the 100x objective.

Both thermal and fast reactors can achieve decent improvement factors in the first few recycles. Both types of reactors can recycle repeatedly. But, the need for additional fissile TRU supply and disposal of curium limits the longer-term performance in thermal reactors.

4.2.3 Thermal/Fast Symbiosis

The previous discussion showed that IMF can lead to rapid heat load improvement factors but is either not sustainable (no blending) or sustainable (blending) with lower performance. Fast reactor cases can be sustainable without blending but lag behind IMF for a few cycles. So, consider the case of one recycle of IMF-NpPu then sustained fast reactor recycle. The first recycle (IMF-NpPu) achieves 2x, as do other IMF cases, when there is only 5 years between

UOX discharge and process by a chemical separation plant. The second recycle (the first in the CR=0.25 fast reactor) raises the heat improvement factor to ~2.8x, higher than either the sustainable pure IMF or pure fast reactor cases. Still to be analyzed is how such symbiotic cases behave after additional recycles. This situation is graphed in figure 4-7, with a hypothetical curve showing the IMF/fast reactor curve approaching the pure fast reactor curve. A key advantage of the IMF/fast reactor combination is that curium does not have to be disposed or stored for Cm244 to decay.

Figure 4-7. Heat improvement factor for a wide range of recycle options
Heat-load improvement factors are conservatively defined assuming residual material is sent to the repository after the number of recycles indicated.

4.2.4 Summary of heat load improvements

In summary, an analysis of repository heat-load improvements versus number of recycles has been completed. Fast reactors appear capable of improvements of ~100x (equilibrium) with 4x achieved after 5 recycles. Thermal reactors with IMF appear capable of improvements of only ~10x (equilibrium) with 3x achieved after 5 recycles, assuming the curium is disposed each cycle; MOX cases were lower. The advantage of recycling in fast reactors versus IMF is not faster acquisition of benefits, but higher equilibrium performance.

This thermal-to-fast differential (10x at equilibrium for IMF versus 100x at equilibrium) arises because of accumulated Cm disposal in the repository, thereby preventing the creation of high neutron isotopes such as Cm244, Cm248, Cm250, and Cf252. More analyses are warranted for the alternative approaches of (a) store curium until it decays and (b) accept the penalties of recycling curium.

Furthermore, combining at least one IMF recycle with fast reactors appears to offer faster benefits than fast reactors alone.

Thermal reactors with MOX appear capable of only 2x heat improvement factors after 7 recycles.

4.2.5 Other repository considerations

The patterns for long-term dose and long-term radiotoxicity appears quite similar to the above trends for long-term heat.[Piet2006]

- An order of magnitude improvement in thermal reactors at equilibrium.
- Two orders of magnitude improvement in fast reactors at equilibrium.
- IMF and low conversion ratio fast reactors have similar performance in the first few cycles.
- MOX gives lower performance than IMF.

4.3 Energy Recovery

Table 4-1 showed that the first recycle pass in thermal reactors provides (at best) a 15% improvement in uranium ore utilization relative to the once-through fuel cycle at 50 MW-day/kg burnup. Substantial increases in energy recovery require repeated recycle passes.

Figure 4-8 shows the uranium improvement factor for 5 recycle passes of MOX and IMF.[Piet2006] The IMF-NpPuAm case has reached a plateau and peaked very slightly at cycle 4. The IMF-NpPu with Am target case does slightly better than the IMF-NpPuAm case. The MOX improvement is still growing at the 5th recycle, but is expected to plateau shortly thereafter.

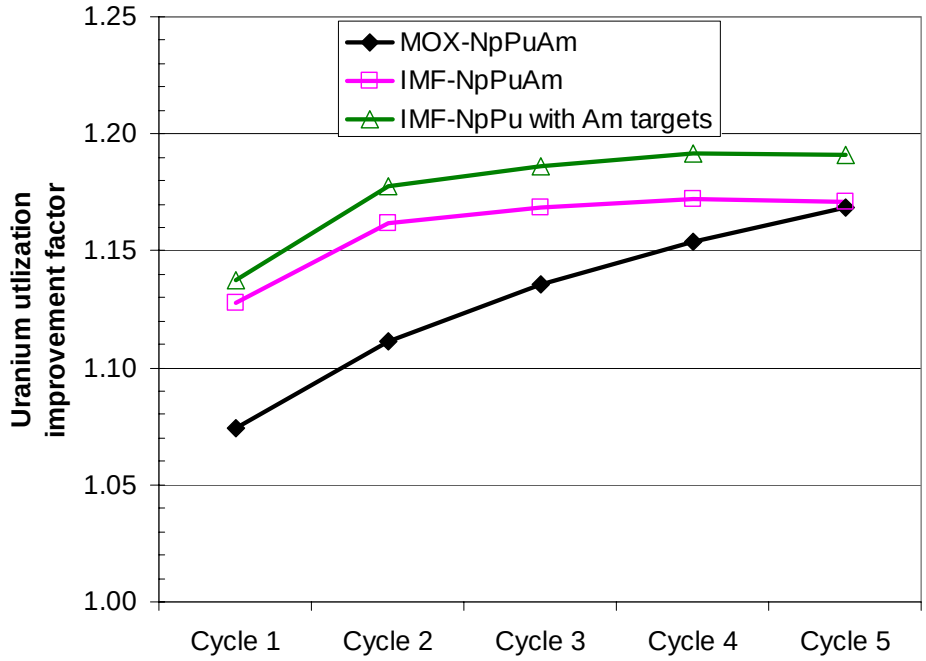

Figure 4-8. Uranium utilization improvement factors for multi-pass IMF and MOX.

At equilibrium, a CR=0.25 conversion ratio fast reactor using TRU from LWRs can achieve only about 1.4 (40% better than once-through). Adding one recycle of IMF or MOX does not appreciably change this result. A breeder fast reactor, however, can achieve factors up to 160x.

So, the basic energy recovery results are as follows:

- At best, thermal recycle may achieve a factor of 1.2, i.e. 20% improvement.
- A low conversion ratio fast reactor (CR=0.25) can achieve slightly better, a factor of 1.4 with or without a recycle pass of IMF or MOX in a thermal reactor.
- A breeder fast reactor (CR=1.1) can achieve two orders of magnitude better.

The two order of magnitude difference between CR=0.25 and CR=1.1 raises the question of how the uranium utilization improvement factor varies between these points. Figure 4-9 shows the answer. The uranium improvement factor increases from CR=0.25 (1.4x) to CR=0.50 (1.6x) to CR=0.75 (2.1x). The factor reaches only 10x at CR=0.97.

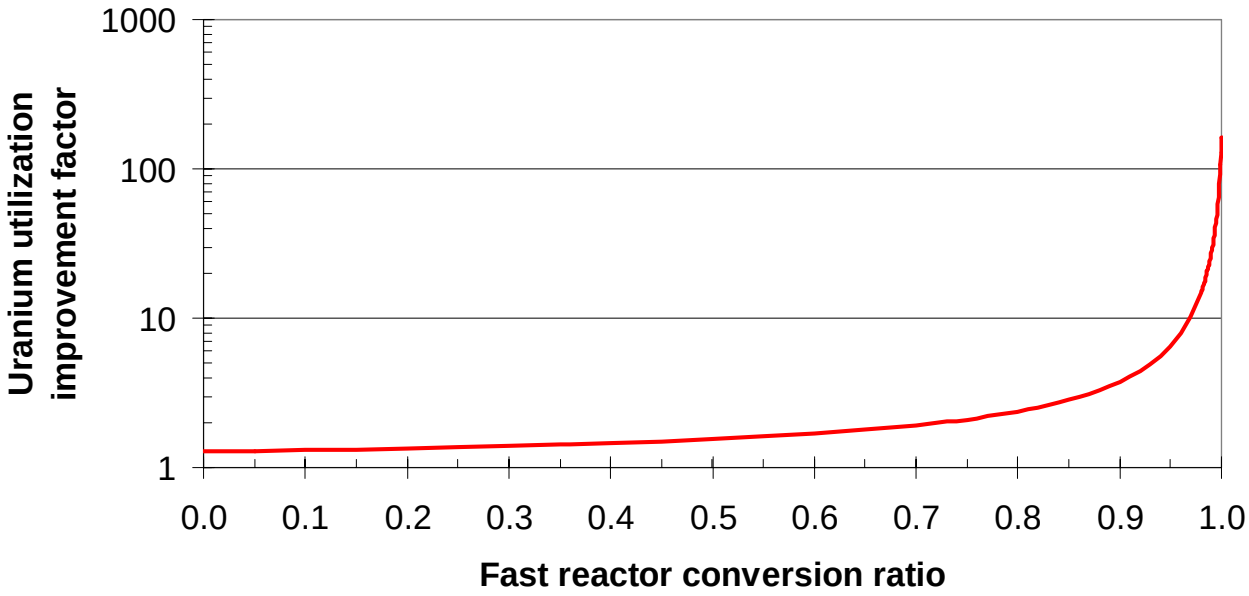

Figure 4-9. Equilibrium uranium utilization factors as function of fast reactor conversion ratio

4.4 Heat, Gamma, and Neutron Emission

The heat, gamma, and neutron emission of recycled fuel is important to both proliferation risk management and to economics. Both aspects are discussed here.

- As these three parameters increase, the proliferation resistance increases.
- As these parameters decrease, the economics becomes more attractive.

Regarding proliferation resistance, all of the compositions explored here are expected to be considered weapons usable. However, the difficulties posed to would-be proliferators does increase as heat, gamma, or neutron emission increase. Yet, the same difficulties can increase cost.

If the heat rate becomes high enough, design of a nuclear weapon becomes more difficult and can eventually become impractical. For example, plutonium mixtures with Pu238 above 80% are considered to generate so much heat that they are not considered weapons usable per the IAEA. Unfortunately, none of the compositions relevant to advanced fuel cycle achieve a comparable heat generation rate, except for pure curium and perhaps some americium-curium mixtures. Yet, even intermediate heat generating compositions would be more difficult than low heat generation options – highly-enriched uranium or pure plutonium – which are available internationally.

As the gamma emission increases, handling becomes more difficult. This is not insurmountable for either would-be proliferators or fuel fabricators, but increases the cost and/or dose to either.

As the neutron emission increases, handling becomes more difficult as with gamma emission. However, neutron emission raises issues in addition to handling dose. High neutron emission makes weapon design significantly more difficult (but perhaps not impossible), assuming one

wants a relatively high yield, high confidence explosion. Poor design can lead to a "fizzle" low yield explosion.

Table 4-2 shows some equilibrium values for heat, gamma, and neutron emission.

Table 4-2. Table of Static Equilibrium Heat (Q), Gamma (γ) and Neutron emission (n) for Fabrication of Recycle Fuels, Normalized to Equilibrium MOX-Pu, on a per mass basis

	Repeated MOX recycle in LWRs	Repeated IMF recycle in LWRs	UOX to fast burner reactor (CR=0.25)	MOX to fast burner reactor (CR=0.25)	IMF to fast burner reactor (CR=0.25)	Fast breeder e.g., CR=1.1
Pu only	Q= **1.0** γ = **1.0** n = **1.0**					
NpPu	Q= **1.9/1.9** γ = **1.9/1.9** n = **1.5/1.2**					
NpPuAm	Q= **5.9/6.0** γ = **13.7/15.1** n = **3.8/2.0**					
TRU	Q= **20/19** γ = **41/39** n = **63,750/71,430**	Analyses required	Q= **39** γ = **76** n = **3,043**	Q= **111** γ = **256** n = **8,659**	Q= **89** γ = **145** n = **8,680**	Q= **0.7/ 1.2** γ = **2.1/ 2.5** n = **38 /32**

- First set of MOX data are from Taiwo2002/Taiwo2006; second set uses the same composition but gamma energy and number of neutrons instead of dose. This shows that the two methods give similar results.
- First set of fast breeder data are from Salvatores2003, second set uses the fuel composition in Piet2006 using gamma energy and number of neutrons. This shows that the two methods give similar results.
- The UOX/MOX/IMF data use the fuel compositions in Piet2006, using gamma energy and number of neutrons. These must be viewed as preliminary approximations.

In all columns – thermal or fast reactors - one expects the heat, gamma, and neutron emission to rank order TRU > NpPuAm > NpPu > Pu, see Appendix A.

Next consider the MOX column. Going from recycling Pu to recycling all the TRU only increases the heat and gamma source by factors of 20 and 40 respectively. It is unlikely that this makes a "show stopper" for either would-be proliferators or fuel fabricators. The neutron source, however, increases by a factor of 63,750.[Taiwo2002] As [Salvatores2003] notes, the penalty for equilibrium compositions is due to recycle of Cm (not so much the Am) into new fuel. Key isotopes include Cm244, Cm248, Cm250, and Cf252. It has not been established whether this is a "show stopper" for either proliferators or fuel fabricators, and, if so, after how many recycle passes have these isotopes accumulated sufficiently to become show stoppers.

Next consider the fast breeder column. The heat and gamma emission for breeder-TRU is similar to MOX-Pu but lower than MOX-NpPu or MOX-NpPuAm. Neither heat nor gamma would seem to be a "show stopper" issue for either would-be proliferators or fuel fabricators. The equilibrium neutron emission for breeder-TRU is ten times higher than MOX-NpPuAm but 2,000x times lower than MOX-TRU.

Next consider the preliminary data for the three cases with a burner fast reactor (CR=0.25). The heat and gamma emission are slightly higher than MOX-TRU. The use of one pass of MOX or IMF before insertion to the fast reactor increases all three parameters (heat, gamma, neutron) relative to going directly from UOX to the fast reactor. But, perhaps more importantly, all of these fast burner reactor cases (CR=0.25) have neutron emission thousands of times higher than MOX-Pu and only an order of magnitude lower then MOX-TRU.

Some observations:

- Detailed study is required for high neutron emission fuels, whether from thermal recycle or fast burner reactors. If the problem is indeed severe,[Briggs2002, NEA2005] then recycling of Cm/Bk/Cf in any reactor other than a breeder may be unwise.
- At equilibrium, the accumulation of curium (and above) in thermal reactors can lead to 4-5 orders of magnitude increase in neutron emission at fuel fabrication relative to Pu-only recycle, which may be an advantage for proliferation resistance and disadvantage for economics.
- The accumulation of isotopes of curium (and above) is both more rapid and higher at equilibrium in thermal reactors than fast breeder reactors. Thus, analyses are warranted to estimate how rapidly gamma and neutron emission increases during the first several cycles. It may be practical to include curium in a few recycles in thermal reactors.

4.5 Proliferation Risk Management

Fuel cycle management includes a number of proliferation risk management issues.[DOE2006, DOE2007] Many are associated with facility design, which is beyond the scope of this report. Most others do not help differentiate among the cases considered in this report.

Besides heat, gamma, and neutron emission, two other issues may be relevant to this report – mixture with fertile uranium and urgency.

Mixing fertile uranium with transuranic material may reduce proliferation risk relative to keeping uranium and transuranic material separate. If there were a criterion that (for example) the fraction of transuranic material must be kept below some fixed percent, it would make the IMF approach impossible. It would also restrict fast reactors to higher TRU conversion ratios, impacting the number of thermal reactors to fast reactors in a mixed recycle scenario.

The other issue relevant to this report is urgency. Per data from the World Nuclear Association website, 31 nations have commercial power plants, only a few have enrichment or chemical separation technologies. At least 8 more - *Egypt, Indonesia, Iran, Israel, Kazakhstan, N. Korea, Turkey, Vietnam* – are actively planning nuclear power. So, as nuclear power is again entering a growth phase, many countries have a choice: buy enrichment and separation technologies or develop their own. The more countries that decide to buy these services from reliable "supplier" nations, the better. Section 5 of this report looks at ways that thermal recycle may help deploy recycling faster.

4.6 Economics

The economic discussion is divided into six parts, as follows:

- The heat, gamma, and neutron emission issue (discussed in section 4.4)
- Mass throughput (section 4.6.1)
- Static fuel cycle differences, ignoring reactor cost differentials (section 4.6.2)
- Importance of thermal versus fast reactor cost differentials (section 4.6.3)
- Equilibrium mix of thermal versus fast reactors (section 4.6.4)
- How thermal reactors can help manage fuel supply in a fast reactor system (section 4.6.5)

4.6.1 Mass throughput

An important economic consideration is the rate that transuranics recirculate in the system. For the same transuranic consumption, the less mass that recirculates, the lower the cost – everything else being equal. For example, the less mass of fuel with a given transuranic composition that requires fabrication, the less expensive the facilities and operations required to produce the fuel. However if the actinide composition of the fuel changes then the fuel fabrication facilities could become progressively more expensive as the safety and shielding requirements dictate going from contact-handled to glove-box to remote-handled. Figure 4-10 compares pure thermal, thermal-fast, and fast recycling options. The mass throughput of fission products is essentially constant as the mass of fission products is fixed per reactor power. The dominant mass component is uranium.

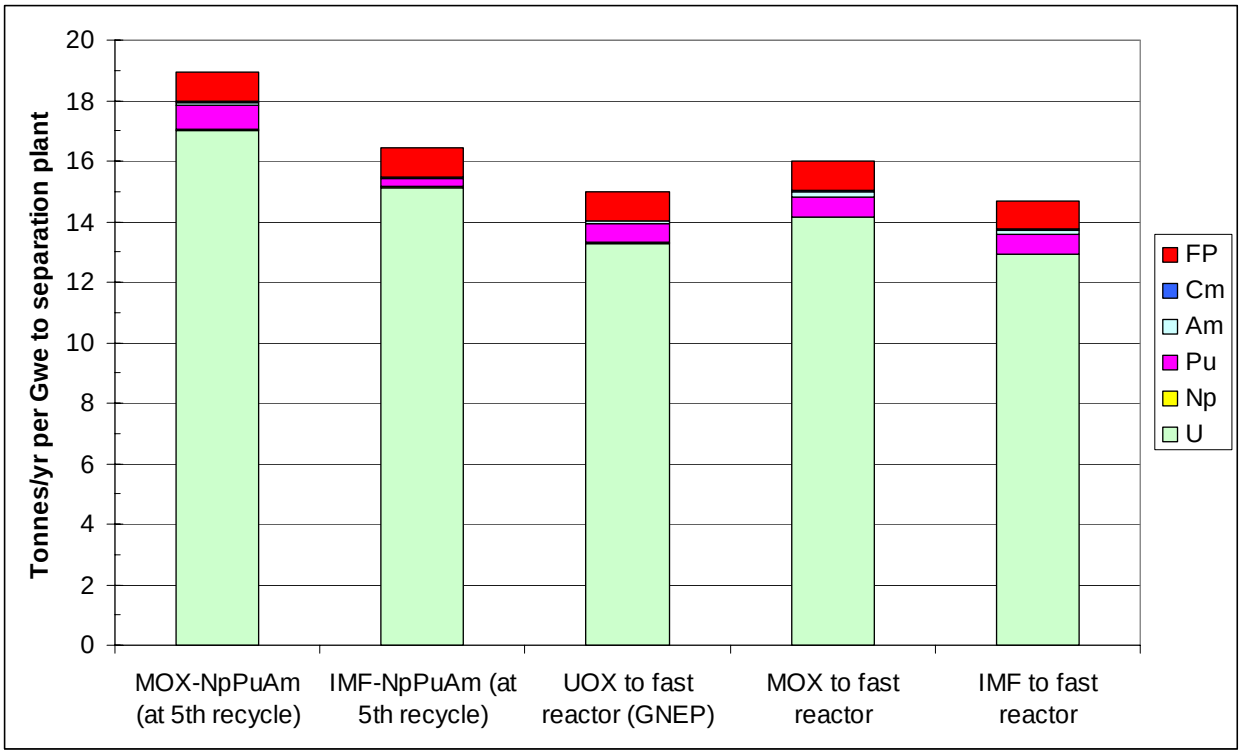

Figure 4-10. Mass Throughput.[Piet2006]

However, uranium is removed early in the separation plant and has relatively low radioactivity. Figure 4-11 compares the mass throughput of only the high radioactivity transuranic elements. The IMF thermal recycle case has substantially lower recirculating Pu flow because of the high consumption rate in the IMF approach. Relative to MOX thermal recycle, the Np and Am flows are also somewhat lower, again because of higher transmutation rates. However, the IMF thermal case has higher Cm flows than MOX thermal because the penalty from the higher transmutation of Np, Pu, and Am is higher accumulation of Cm. A detailed economic trade off among the options that weights the cost as a function of individual elements (presumably Cm costs more per tonne separated and fabricated than Am, etc.) has not yet been performed but can result from future GNEP technology studies.

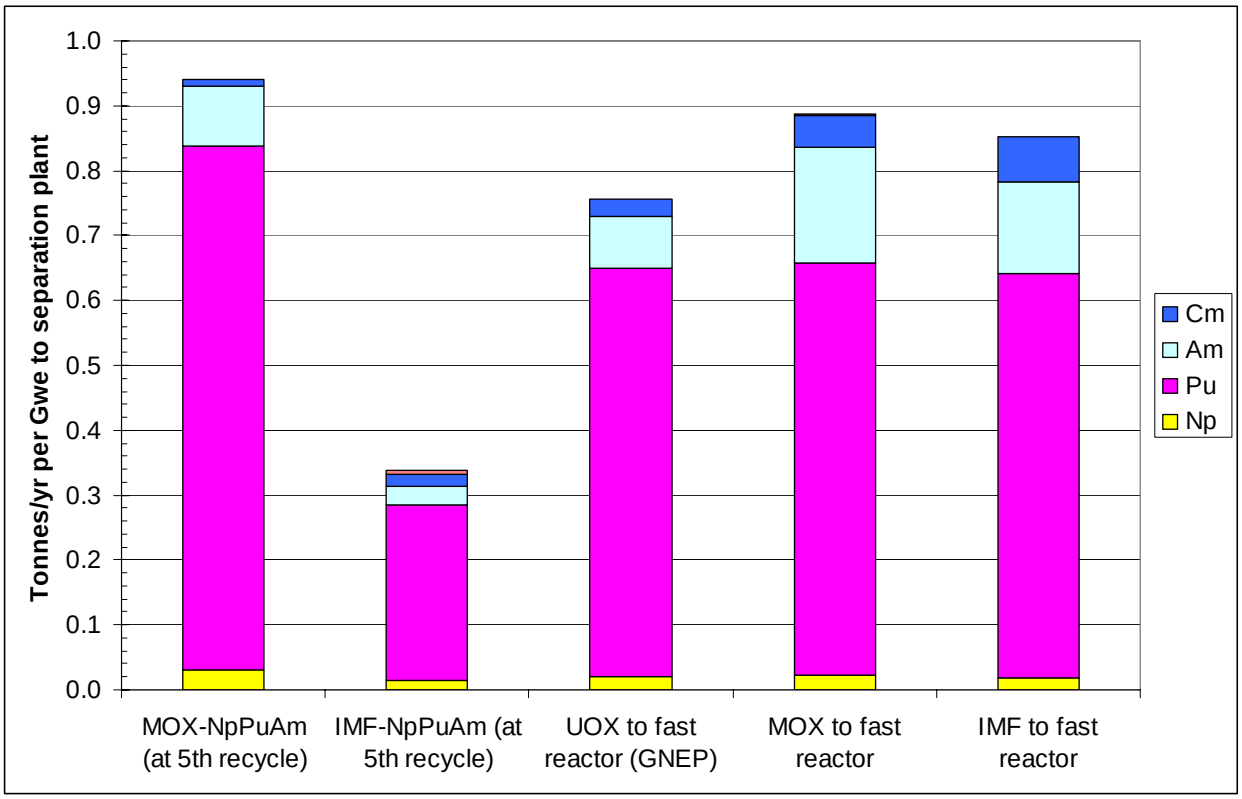

Figure 4-11. Mass Throughput of Transuranic Elements.[Piet2006]

4.6.2 Fuel cycle differences, ignoring thermal-fast reactor cost differentials

Table 4-3 summarizes fuel cycle cost ranges for key strategies at static equilibrium.[Shropshire2006] The intervals represent the 95% cost uncertainty bounds for equilibrium fuel cycles for each strategy. The cost ranges indicate significant cost uncertainties across all strategies and a significant overlap of the cost distributions across the fuel cycle strategies. The economic analysis showed large cost uncertainties with all the fuel cycle strategies, with levelized equilibrium fuel cycle costs ranging from approximately 5 to 21 mills/kWh.

Table 4-3. Fuel Cycle Cost Estimates from Static Equilibrium Analyses

Strategy and Variations	Once through	Recycle in thermal reactors only		Sustained thermal/fast recycling		Sustained fast reactor recycling
		Once	Repeated	Recycle in thermal & fast	Recycle in fast only (GNEP)	
Technologies assumed in the economic analyses						
Thermal reactors	LWRs					-
Fast reactors	-			Sodium cooled		
Thermal reactor fuels using enriched uranium	Uranium oxide					-
Thermal reactor fuels using recycled TRU	-	MOX-TRU		MOX-NpPu	-	
Fast reactor fuels using recycled TRU	-			TRU metal-TRU		
Separation technologies	-	UREX+		UREX+ Am/Cm separation for MOX fuels; pyroprocessing for metal fuels		
Objective: Improve fuel cycle management, while continuing competitive fuel cycle economics and excellent safety performance of the entire nuclear fuel cycle system.						
Fuel cycle cost ranges (within 95% uncertainty bounds)	5.3 to 8.1 mills/kW-hr	9.2 to 18.0 mills/kW-hr		8.6 to 11.6 mills/kW-hr[7]	6.1 to 10.2 mills/kW-hr	6.3 to 11.3 mills/kW-hr
Major uncertainties not included						
All reactor capital costs the same	-			Needs new reactor types. Fast reactor cost differential versus LWRs (and uncertainties thereof) is not included		
Fast recycling based on metal fuel	-			Calculations based on metal fuel for fast reactors, oxide fuel for fast reactors has not been assessed.		
Recycle cases assume homogeneous fuels	-	Recycle assumed done with homogeneous fuels that recycle the elements identified that for case. This requires use of glove-box fuel fabrication for NpPu MOX fuels and remote handled fuel fabrication for thermal recycle of AmCm targets. There may be advantages to segregating high radiation americium and curium into targets so that only a few percent of the material requires remote fabrication while the rest (U, Np, Pu) does not. This would require additional chemical separations and development of additional fuels or targets.				
LWR licensing costs based on routine UOX	-	Potential additional utility costs (e.g. relicensing) needed to use MOX fuels in LWRs was not included.			-	
LWR recycling based on MOX	-	Calculations based on MOX; IMF has not been assessed. IMF costs may be lower because mass throughput is 2-3x lower than MOX and smaller fraction of fuel must be made remotely.			-	
Costs for additional repositories	Future repositories assumed to cost the same as the first		-			
Major uncertainties included						
For all cases	The cost range reflects the unknowns including reprocessing technology performance and cost, fast reactor performance, geologic repository costs, and waste form/disposal unknowns.					
Major uncertainties	Pricing of uranium and fuel services; costs for partially used fuel disposition.	Technology uncertainties for separation and refabrication.		Technology uncertainties for separation, refabrication, and fast reactors.		
Main cost discriminator	Uranium mining and milling, ±1 mills/kW h	The main cost discriminator for the closed fuel cycles is recycled fuel fabrication, varying from ±3 mills/kW h. The impact from separations costs are on par with the costs of process waste conditioning and disposition at ±0.5 mills/kWh.				

[7] The 2-tier thermal and fast recycle alternative was based on the same methodology and cost basis as the other four strategies; however, this analysis was performed after the cited report [Shropshire2006] was released.

A few uncertainties require explicit mention in the text, as follows:

- There is a large economic uncertainty associated with the cost of additional geologic repositories; this primarily impacts the cost uncertainty for the once-through strategy. The viability of the once-through fuel cycle requires establishing the viability (and cost) of siting and constructing additional geologic repositories.
- Separation and waste handling costs are uncertain; all recycle strategies depend on effective separation processes and economically viable waste treatment, packaging, and disposal. There are unknown cost risks due to limited technical process maturity and operational experience with pyrochemical separation and fabrication, and to a lesser degree—aqueous separation. Separations technology for IMF depends on the matrix material, and may require new processes.
- The costs of newly developed fuels that can use recycled transuranic elements are uncertain; all recycle strategies require new types of fuels. The fraction of all fuel used that must be newly developed varies considerably among the recycle options.
- Analyses of the uncertainty of the thermal/fast and fast reactor costs are beyond the scope of this report.
- All analyses are for a static equilibrium, no dynamic effects are included such as one part of the system preventing another working at full capacity.

4.6.3 Importance of thermal versus fast reactor cost differentials

The Very High Temperature Reactor (VHTR) and LWRs are both thermal reactors, and may use similar fuel cycles. The penetration of the VHTR in to the current LWR market (electricity) and the penetration of VHTR into the transportable energy fuel market (via hydrogen production) depend primarily on the comparative economics to competing energy supply sources; in those contexts the cost uncertainties associated with VHTR are critical. But, from the fuel cycle perspective, strategies shown on LWRs could also work with VHTRs. For example, both LWRs and VHTRs offer the potential to achieve conversion ratios near zero, that is, preferentially consume transuranics with little or no new TRU produced from uranium in the fuel, e.g. inert matrix fuel (IMF). The effectiveness of such approaches depends on much of the core can safely operate on IMF (see Section 4.7.1) and how long each type of IMF can be kept in each type of reactor, which is the subject of ongoing research.

The cost uncertainty of fast reactors is very relevant to the thermal/fast and fast-recycle strategies because they require fast reactors to be viable. The importance of any premium on the costs of fast reactors compared to thermal reactors depends on the percent of fast reactors required to make the strategy work. Fast reactors potentially could be designed with conversion rates as low as CR ~ 0.25 up to CR>1. The lower the conversion ratio, the faster TRU can be consumed with fewer fast reactors required, hence less system cost sensitivity to fast reactor cost.

4.6.4 Equilibrium mix of thermal and fast reactors

Although the above analyses do not address the potential thermal-fast reactor cost differentials, it is possible to identify which cases are more sensitive to fast reactor costs because the cases differ in the number and percent of fast reactors required. Figure 4-12 shows the equilibrium mix of thermal and fast reactors as a function of fast reactor conversion ratio for the IMF case, the MOX case has not been assessed. The data points are from E. Hoffman.[Hoffman2006]

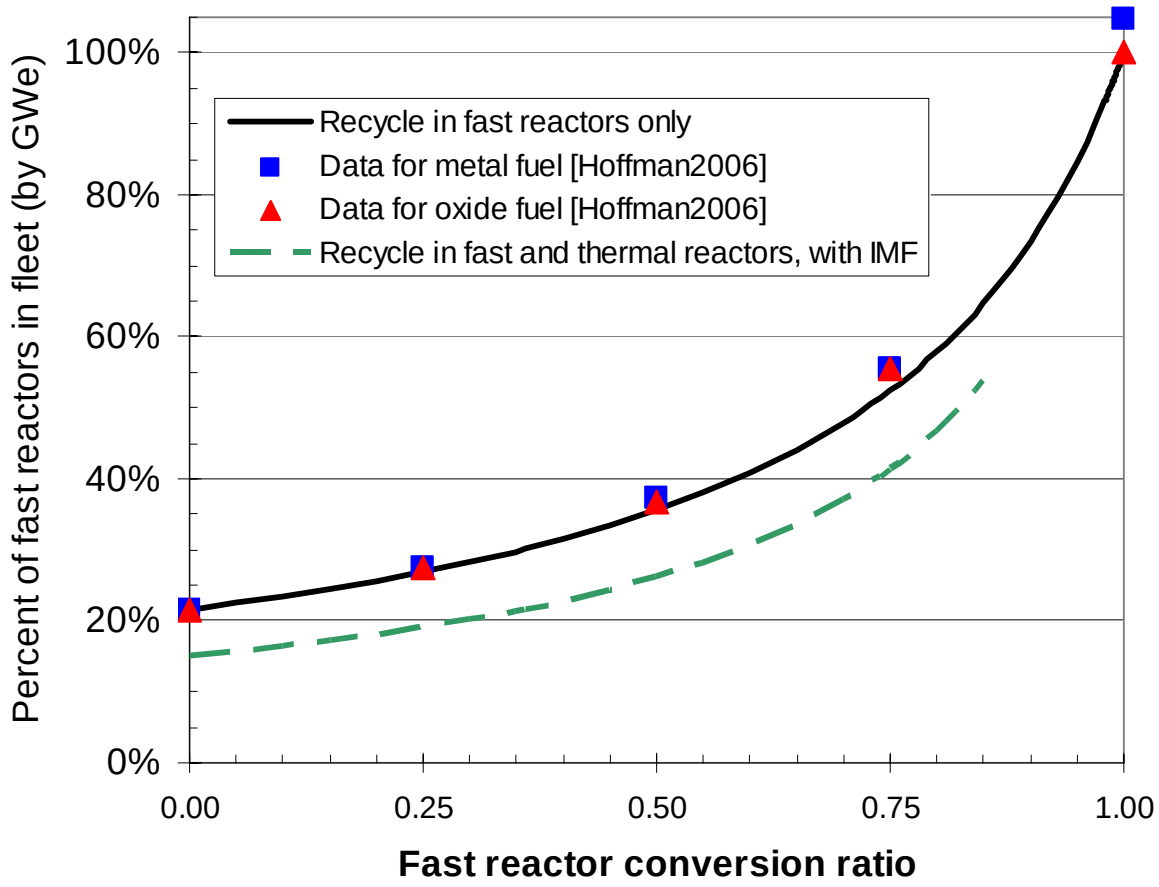

Figure 4-12. Equilibrium fraction of fast reactors in fleet.

At CR=0.25, the equilibrium is 27% fast reactors and 73% LWRs. The 27% result can be reduced to 19% by adding recycle in LWR-IMF or 20% with LWR-MOX. This would increase R&D costs because the R&D needed for the GNEP approach would still be needed, plus the R&D for the LWR-IMF or LWR-MOX technology. Section 5 shows how these results change in dynamic analyses; however, the rank ordering stays the same.

4.6.5 Thermal reactor role in managing a fast burner system

If a thermal reactor is recycling TRU but a shortage of TRU develops, the reactor can be shifted back to enriched uranium oxide if there is world-wide UOX stockpiles and idle uranium

enrichment capacity. Conversely, if an excess of TRU develops, more reactors can be shifted from uranium oxide to recycled TRU.

There are three key differences that fast burner reactors have relative to the above thermal case. First, a significant fraction of the TRU supply for the fast reactors (and their used fuel separation plants) comes not from other fast reactors but from the LWRs (and their used fuel separation plants). The two portions of the overall fleet must work together. Second, under GNEP, the objective is that fast reactors would be located only in "fuel supplier" nations, whereas thermal reactors would be ubiquitous. Thus, the number of fast reactors in individual fuel supplier nations has to be balanced against thermal reactors in other countries. Third, it is generally considered very expensive to fuel a fast reactor with enriched uranium (the required U-235 enrichment is several times higher than in a thermal reactor), so if the TRU supply is inadequate, there is no second fuel (enriched UOX) as an attractive backup.

If a fast burner reactor system is in near equilibrium and then loses or gains TRU supply, such as by shutdown of separation facilities or gain/loss of international partners (and hence the TRU from separation of their fuels), the equilibrium in figure 4-12 must be adjusted. Figure 4-13 shows three possibilities:

- Use or increase TRU stockpiles, especially if legacy used LWR fuel is available,
- Increase or decrease the CR of some fraction of the fast reactor fleet, or
- Add or drop fast reactors – a long-time horizon adjustment.

The stockpiles could be used fuel rather than TRU if separation capacity is adequate and if the stockpiles are accessible by the supplier nation.

The hypothetical possibility of using enriched uranium oxide to fuel the fast reactors is not shown due to high cost.

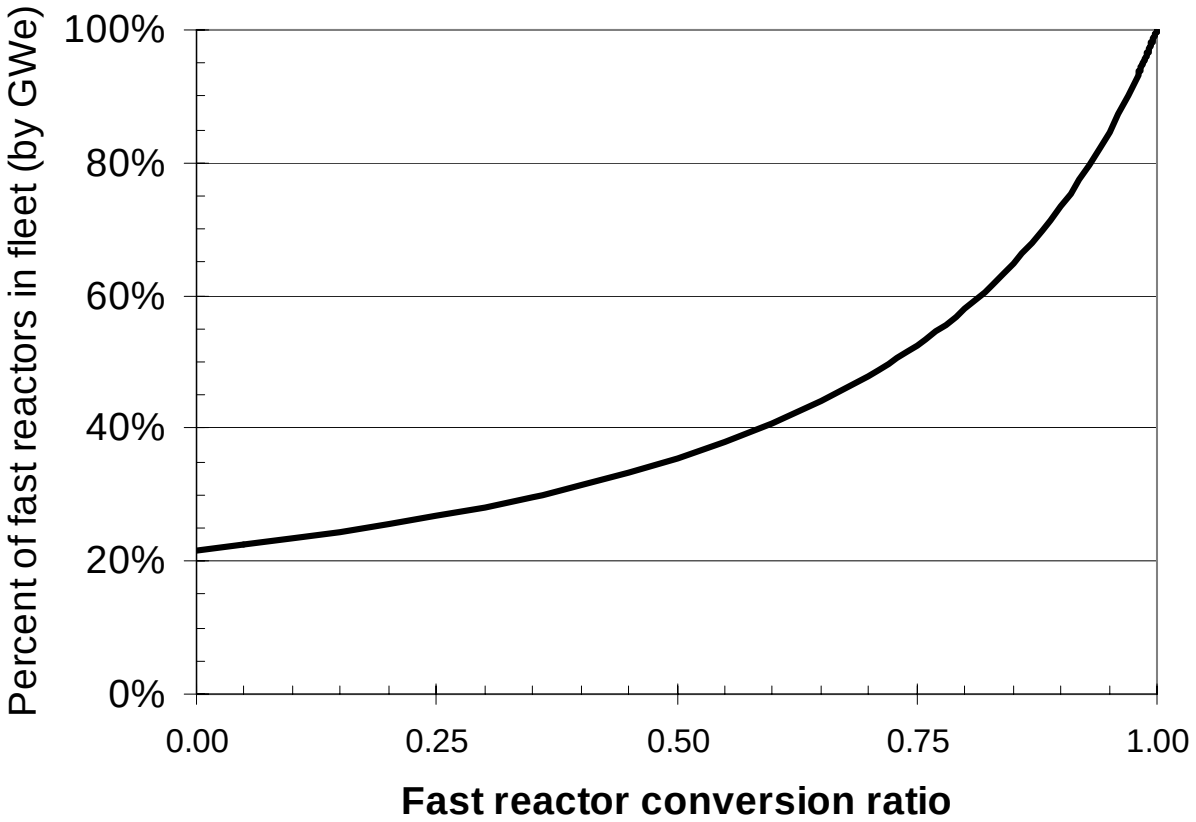

Figure 4-13. Three possible ways to adjust a system if the TRU supply changes. Red arrows show transuranic supply perturbations away from the equilibrium; green arrows show possible restoration of equilibrium.

Table 4-4 shows a quantitative example for a hypothetical loss of transuranic supply from 6 GWe of LWR, e.g., if the country with a small reactor fleet were part of a GNEP consortium but chose to leave it. The higher the CR operating point of the system prior to such a perturbation, the higher the number of ABRs impacted. (The higher the conversion ratio, the lower the transuranic consumption of each ABR.) And, in the case of a CR-shift approach, as the shift is implemented across more ABRs, the less the CR shift required for any single ABR. For CR ≥ 0.50 and a CR-shift constrained to only 3 GWe of ABRs, those ABRs would need to be shifted to breeder mode, i.e., at least 3 GWe of ABR can no longer be supported by TRU from LWRs.

Table 4-4. Hypothetical Adjustments to an Equilibrium System if 6 GWe (LWR) left the System

	CR=0.00	CR=0.25	CR=0.50	CR=0.75
Use TRU stockpile to provide 10-year buffer	15 tonnes-TRU			
Shift the CR of				
3 GWe of fast reactors to …	0.55	0.79	breeder	breeder
10 GWe of fast reactors to …	0.17	0.42	0.67	0.92
30 GWe of fast reactors to …	0.06	0.30	0.59	0.83
Shutdown GWe of fast reactors	1.7	2.2	3.3	6.6

If thermal recycling is part of the system, figure 4-14 shows an additional way to adjust to a gain or loss of TRU supply: adjust the number of thermal reactors using IMF or MOX. If desired, a new equilibrium can be established later as in previous figure 4-11.

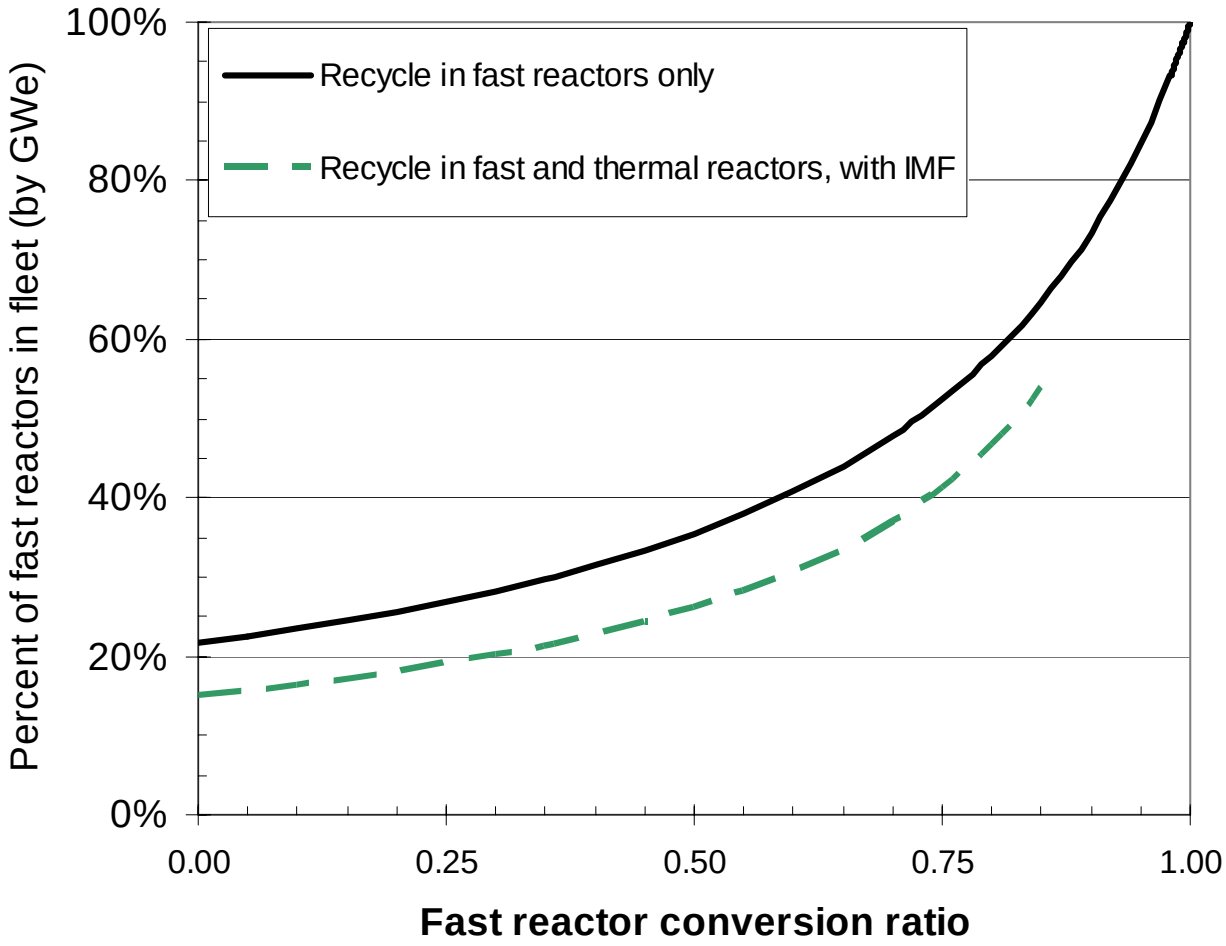

Figure 4-14. Additional way to adjust a system if the TRU supply increases or decreases if thermal recycling is part of the system.

4.7 Safety

The safety issues are considered in five parts, as follows:

- The heat, gamma, and neutron emission as it impacts worker safety. It also gives an indication of relative source term in off-normal events.(discussed in section 4.4)
- Mass throughput because more mass indicates more potential for accidents and spills.(section 4.6.1)
- Safety in the reactor portion of the system (section 4.7.1)
- Safety in separation and fuel fabrication facilities (section 4.7.2)
- Transportation (section 4.7.3)

4.7.1 Thermal reactor role in managing a fast burner system

With regard to reactor safety, Table 4-5 lists safety constraints based primarily on void reactivity coefficients. It is important to note that these limits are based on the first recycle pass (MOX or IMF); little work has been done on subsequent passes. We do have these expectations.

- Systems with enriched U-235 reduces the problem with including TRU in the core [Salvatores2003]
- As the Pu vector in MOX-cores degrades with subsequent recycles, the problems get worse [Salvatores2003]
- Including Np or Am or Cm – impact negative.

Table 4-5. Thermal Reactor Safety Constraints on MOX/IMF [adapted from Todosow2004]

	single-pass MOX			single-pass IMF		
	% of reactors that can use	% of core	% of all fuel in fleet (reactors x core)	% of reactors that can use	% of core	% of all fuel in fleet (reactors x core)
Current PWRs and BWRs	50%	33%	16%	25%	25%	6%
Future PWRs and BWRs	100%	100%	100%	50%	100%	50%

4.7.2 Separation and fuel fabrication facilities

Previously, safety experiences with separation and fuel fabrication facilities were analyzed.[Cadwallader2005] In the context of this report, probably the dominant safety discriminators among options are heat, gamma, and neutron emission, discussed in Table 4-2.

4.7.3 Transportation

Table 4-6 compares the relative amount of transport of used and recycle fuels. The issue is not thermal or fast recycle *per se*, but rather the location of separation and fuel fabrication and the refueling interval in fast reactors. The configuration of the thermal part of a recycle system is relatively well defined - thermal reactors located as they are now, low radioactivity uranium oxide fuel fabrication located a few places around the country, and one or more new centralized UREX+ plants to separate used LWR fuel.

Table 4-6. Comparison of Relative Transport of Used and Recycle Fuels

Strategy and Variations	**Once through**		**Recycle in thermal reactors only**		**Sustained thermal/fast recycling**		**Sustained fast reactor recycling**
	Current burnup	**Doubled burnup**	**Once**	**Repeated**	**Recycle in thermal & fast**	**Recycle in fast only (GNEP)**	
Objective: Improve fuel cycle management, while continuing competitive fuel cycle economics and excellent safety performance of the entire nuclear fuel cycle system.							
Minimize transport of used and recycle fuels	No change	50% lower	Little change	Off-site recycling – little change			
				On-site recycling could reduce transport to about 10% of once-through			

There are two major alternatives for the fast reactor configuration.

- Use a centralized UREX+ plant to separate used fast reactor fuel, especially if the fast reactor uses an oxide fuel.
- Use on-site pyroprocessing plants to separate used fast reactor fuel and fabricated new fuel, especially if the fast reactor uses metal fuel. These plants would be co-located with groups of fast reactors.

The difference arises because of the current assessment that, unlike aqueous separations plants, pyroprocessing plants would not benefit significantly from the scale-up afforded by centralizing capacity. On-site separation and fuel fabrication would significantly reduce the amount of transportation of used and new fast reactor fuel. However, this approach means that each group of reactor sites would have separation and fuel fabrication plants. The economic and safety tradeoffs have not yet been assessed.

5. TIME-DEPENDENT ANALYSES

Three of the four potential roles considered for thermal recycling – stop-gap, mixed, backup – are envisioned as temporary alternatives or add-ons to recycling in fast reactors. The fourth – pure thermal – is defined as a permanent alternative. Thus, exploration of the value of these possibilities require time-dependent analyses to probe questions such as what happens if thermal recycling is continued for several decades or the first UREX+ plant starts up but the first ABRs performance leads to delay in ABR deployment. The analyses were performed with the Verifiable Fuel Cycle Simulation Model (VISION) model.[Jacobson2006, Yacout2006]

The following analyses should be considered illustrative in terms of system behavior, not definitive quantitative values. In general, quantitative results are also sensitive to the illustrative parameters that specify time lags in the system, e.g., 2 decades from discharge of UOX to MOX/IMF to first possible use to start up a new ABR. Another example: if stop-gap is implemented, associated MOX/IMF facilities must be built to close the "gap" but then "stop" later. How long do they operate after ABRs come on line? The simulations in this report assume they run 30 years, presumed to be a minimum time to recover the economic investment.

5.1 Cases Considered

The analyses in this section were conducted on the following options:

- Separated transuranics direct to ABR
- 1-pass MOX-NpPu or IMF-NpPu, then ABR
- Multipass MOX-NpPuAm or IMF-NpPuAm, no ABRs

The first is the GNEP approach. The second is used to explore stop-gap, mixed, or backup recycling. The third is used to explore the pure-thermal approach.

The most important parameters used in the calculations are summarized in Table 5-1. Details are listed in Appendix C.

Table 5-1. Major Analysis Parameters

Parameters	Illustrative parameters for the GNEP strategy (UOX direct to ABRs)	Rationale
Nuclear power growth rate	2.25%/year	Illustrative parameters for ABR case specified by DOE in early February 2007.
Date first new LWR on line	2015	
Date Advanced Fuel Cycle Facility on line	2016 (*)	
Date geologic repository opens	2017 (0 to 3 kt/yr acceptance rate in 5 years)	
Used LWR fuel assumed permanently emplaced in repository, not retrieved	63 kt	
Date first UREX+ on line (separation capacity for used LWR fuel)	2020 (assumed to provide 2 kt/yr after a 5-yr rampup)	
Date first ABR on line	2021 (0.36 GWe or 1.0 GWth)	
Subsequent ABR on line	2031 (limited to 1 GWe/yr for the first five years, 2 GWe/yr for the next ten, and then limited only by TRU availability)	Wait several years after first ABR before building more; introduce in a modest fashion.
ABR conversion ratio	0.25	Only CR=0.25 data are available for these three cases.
(*) In addition, the AFCF was assumed in this report to provide a product of 0.1 kt-TRU/yr to make fuel for the first ABR. VISION will not allow new fast reactors without a prior supply of transuranics for fuel, so this was necessary even though the initial core of this ABR may come from other sources.		

To explore the benefits of thermal recycle, five approaches were defined:

- **GNEP**, first ABR in 2021, subsequent ABRs in 2030, recycle in ABRs only (Table 5-1).
- **Stop-gap**, first ABR in 2031 rather than 2021 (1 decade delay), start MOX/IMF in 2020 to fill the "gap", "stop" MOX/IMF after 30 years.
- **Mixed**, first ABR in 2021, start MOX/IMF also in 2021, thus using a symbiotic mix of fast and thermal reactors to recycle fuel, reducing the number of fast reactors required.
- **Backup**, first ABR in 2021 but subsequent ABRs delayed to 2051 instead of 2031 (2 extra decades), start MOX/IMF in 2030 to reduce the accumulation of TRU while waiting for subsequent ABRs.
    - **No-backup variant**, do not start MOX/IMF, but since the UREX+ plant already started, continue to operate it, accumulating TRU until ABRs eventually come on line.
- **Pure thermal**, start MOX/IMF in 2020 instead of ABRs.

This defines 10 cases: GNEP, no-backup, and 2 each (MOX and IMF) for stop-gap, mixed, backup, and pure thermal.

Some other important time lags include the following:

- Minimum time between reactor discharge and shipment elsewhere: 5 years[8]
- Separation and fabrication time: 1 year
- Number of years worth of fuel in the initial cores: 4 years (ABR), 5 years (LWR)
- Time between ordering reactor and being on line: 5 years
- Time between ordering UREX+ separation plants and being on line: 5 years

The initial core parameter depends on the number of batches/cycles, cycle length, etc. The other parameters are user input. These time lags are meant to be illustrative, but as discussed later they do impact the results. Therefore, the numerical results must be viewed as illustrative, not definitive.

For example, for used LWR to ABR, the minimum time lag is 7 years: 5 years cooling plus 2 in separation and fabrication. There may be additional time lags if multiple years of fuel accumulation are needed to obtain sufficient new fuel for a core to start up the next ABR or if separation capacity is not adequate.

For used LWR to MOX/IMF to ABR, the minimum time lag is 18 years: 5 years cooling, 2 in separation and fabrication, 4 in LWR, 5 years cooling, 2 in separation and fabrication. In this case, in current simulations, the available UREX+ capacity is first used for LWR-UOX to LWR-MOX. Thus, in the UOX-MOX/IMF-ABR cases, the fueling of startup cores for ABRs depends on the TRU harvested from discharged UOX at least 18 years earlier – if there are no additional bottlenecks in the simulation from inadequate separation capacity, fabrication, etc.

5.2 Decide-to-Build Algorithms

With the above parameters specified, the next most important parameters determine when new separation facilities and reactors are built. These decide-to-build algorithms are somewhat complex, but vital to make time-dependent simulations realistic. Real systems have time lags between decisions and when new plants are on line; the simulations try to capture this complexity that influences the manageability of fuel cycle options. Indeed, the potential value of "stop-gap" and "backup" recycling depends on whether the timing of decisions to implement either might make sense relative to when hypothesized difficulties with fast reactors might occur.

The separation technology for LWR fuels (UOX, MOX, or IMF) is assumed to be UREX+. After the first UREX+ plant (Table 5-1), additional capacity is added in the simulations with the following guidelines.

- Plants are treated as having 100% capacity factor, so actual plants would be larger.
- Build sufficient capacity to eliminate accessible stored used fuel by 2100 (within 4 kt-fuel of zero.) "Accessible" includes used fuel in dry storage, whether at reactors, at a centralized facility, or at the repository. It does not include a minimum 5-yr storage at reactors nor the 63 kt assumed permanently emplaced in the repository.

[8] Transportation studies now in progress may identify the need for longer delays to allow more cooling time, depending on the fuel and burnup level.

- Capacity is always increasing, e.g., plants are not brought on line to use for a few years and then turned off. New plants are kept running.
- Capacity is added in units of 1, 2, or 3 kt/yr, that is, no more than 3-kt/yr increase in a single step.
- Capacity is not added if it would lead to more than 1 kt/yr underutilization of separation capacity in subsequent years. This was done manually. Future versions of VISION may incorporate more sophisticated automatic algorithms, but if so, they should account for the economic penalties of either over-building or under-building separation capacity. The former leads to low separation plant capacity factors; the later either starves fast reactors or inhibits new ABR construction.
- Plants are ordered 5 years before they come on line.

The separation technology for ABR fuels is not specified. The capacity to separate used ABR fuel is assumed to be tailored to match ABR construction. This is most obviously the case if separation of used ABR fuel is co-located with ABRs. That is, when ABRs are built, so too are associated separation and fuel fabrication plants.

The fabrication capacity for UOX, ABR, MOX, or IMF fuels are assumed unconstrained.

In the simulations presented here, reactors (LWRs or ABRs) must be ordered 5 years before they come on line, nominally 1 year for licensing and 4 years for construction. New reactors are ordered by comparing the desired level of nuclear power 5 years in the future versus the existing capacity, reactors in the pipeline (licensing or construction), and pending retirements.

To determine what fraction of new nuclear power plants ordered are LWRs or ABRs in a given year, the model takes the minimum of the ABR fraction requested by the user versus the TRU supply available to support more ABRs.

- The needed TRU supply takes into account both the amount of TRU to fabricate the first core of the ABR and the continuing TRU makeup each year.
- The available TRU supply for yearly makeup is the minimum of the TRU being discharged by currently operating LWRs and the current UREX+ separation capacity. If this is greater than the yearly makeup required by the currently operating ABRs, more ABRs may be built, subject to the other constraints. Whenever more TRU is produced than required by currently operating ABRs, it goes into a TRU stockpile.[9,10]
- The available TRU supply for first cores is the current TRU stockpile and/or the excess TRU (separation plant output minus ABR fuel requirement) in a given year.

5.3 Timelines

Figures 5-1 through 5-5 show the requested timelines for GNEP, stop-gap, mixed, backup, pure thermal. Each GNEP timeline simply graphs several parameters from Table 5-1 and Appendix C.

[9] The assumption (Table 5-1) that 63 kt-SNF stays in the geologic repository substantially reduces the excess used fuel inventory that must be processed.

[10] In addition, if the stockpile is sufficiently large to provide fuel for the lifetime of an ABR, such an ABR can be built and that TRU considered mortgaged so that it is not used as the basis for starting other ABRs.

It is stressed that the timelines are what is requested in the simulation. The simulation then produces results consistent with all the constraints. In the simpler cases (UOX to ABR only, UOX to MOX/IMF only), the simulation behavior is close to what is requested. In the more complex cases (UOX to MOX/IMF to ABR), the requested behavior generally does not occur because of the interwoven constraints. Such difference are themselves informative about the value (or lack thereof) of various thermal recycling roles, which is the purpose of the report.

For **GNEP**, to match illustrative parameters, after 2015 one "orders" about 0.5% of new nuclear plants to be fast reactors, this triggers VISION to build a 0.36-GWe ABR, which comes on line in ~2021.

Figure 5-1. Illustrative requested timeline for GNEP.

The **stop-gap** (figure 5-2) requested timeline assumes that the ABR program is delayed 1 decade relative to the above GNEP case, but the UREX+ program remains on schedule. As a stop-gap, MOX/IMF is implemented in 2020 and terminated in 2050. This gives the MOX/IMF fabrication plant a 30-year lifetime. That is, if a decision is made to start MOX/IMF, thereby requiring construction of associated facilities; it is presumed appropriate to simulate continued use of MOX/IMF to recover the financial investment.

Figure 5-2. Illustrative requested timeline for stop-gap approach.

The **mixed** recycle requested timeline (figure 5-3) assumes that both the UREX+ and ABR programs proceed as planned, but that MOX/IMF is also implemented, thereby allowing both reactor types to recycle transuranics. Fewer ABRs are required than if MOX/IMF is not implemented. These simulations do not allow the ABRs to come on line quickly because ABRs are assumed in the current simulation to use only TRU recovered from discharged MOX/IMF. Therefore, although the ABR timeline in figure 5-3 looks the same as for GNEP (figure 5-1), the actual ABR build rate is substantially lower. Future VISION modifications should allow for a dynamic partition of the TRU from UOX – some to MOX/IMF – some to ABRs.

Figure 5-3. Illustrative requested timeline for mixed recycle.

The **backup** timeline (figure 5-4) assumes that both UREX+ and ABR programs proceed as planned, except the observed performance for the first ABR is presumed inadequate to warrant ordering additional ABRs. Therefore, instead of subsequent ABRs coming on line in 2030, they are assumed delayed 2 extra decades to 2050. As a backup, MOX/IMF becomes operational in 2030 and continues. Deploying MOX/IMF in 2030 assumes that a decision to do so is made only a few years (~2025) after the first ABR comes on line in 2021 and that the technologies are ready. The backup timeline also assumes that once MOX/IMF is started, it continues on the assumption that market interest in ABRs is lower than in the GNEP case.

Figure 5-4. Illustrative requested timeline for backup.

As an alternative, we also simulated what happens if ABR deployment is delayed but there is no MOX/IMF available as backup.

The **pure thermal** timeline (figure 5-5) assumes the UREX+ program proceeds as in the GNEP strategy case, but instead of ABRs starting in 2020, multipass MOX or IMF start in 2020.

Figure 5-5. Illustrative *requested* timeline for pure thermal strategy.

5.4 Separation Capacity

To emphasize that the ABR build rate (after 2045) is limited only by transuranic supply, we discuss the separation capacity growth first and then the ABR growth (section 5.5). The separation capacity resulting from the decide-to-build algorithms discussed in section 5.2 is shown in figure 5-6.

Separation capacity is denoted in the model in units of kt/yr of used fuel, with no differentiation by composition of the used fuel, except that separation of LWR and ABR used fuel is accounted for separately. The requested UREX+ separation capacity in figure 5-6 after 2040 was slightly higher for GNEP than for the other cases to ensure adequate supply of transuranic fuel to construct and operate ABRs (fresh cores) and thus maximize that case's performance. It turns out this extra requested capacity was not needed. Section 5.9 describes one of the results of the analysis, how much separation capacity was actually used.

Figure 5-6. Requested UREX+ separation capacity as function of time

5.5 Fast Reactor Capacity

Figure 5-7 shows the growth of fast reactors.

Figure 5-7. Fast reactor capacity from 2020 to 2100

Figure 5-8 zooms into the initial period of fast reactor deployment. For **GNEP**, as desired, the first ABR comes on line in 2021 at 0.36 GWe. No additional fast reactors come on line until 2030. The ABR capacity ramps at slightly less than 1 GWe/year until 2035 and then ramps at slightly less than 2 GWe/yr. Transuranic fuel supply becomes a constraint in 2039[11]. A few years later, after new UREX+ capacity has fed the pipeline, ABR growth resumes.

Figure 5-8. Fast reactor capacity

The **stop-gap** case, as defined, has a 1-decade delay in the ABR component of the program, so the above GNEP dates are shifted 1 decade. However, the deployment of MOX in 2030 uses some of the transuranic material from the UREX+ plant. So, the deployment of ABRs is constrained earlier in the 2-GWe/yr phase (about 2043) than for the GNEP case. Later, sufficient UREX+ capability has been added and the stop-gap recycling in thermal reactors has ended and the growth of ABRs increases.

The **mixed** case, as defined, implements MOX or IMF at the same time as ABRs. The growth of ABRs is constrained shortly after 2030 with IMF and about 2035 with MOX.

After the first ABR in 2021, the **backup** case, as defined, involves a 2-decade delay in subsequent ABRs from 2030 to 2050. As with the GNEP case, the growth of subsequent ABRs is constrained to 1 GWe/yr for five years and then 2 GWe/yr for ten years. However, deployment of backup recycling constraints ABR growth below 2 GWe/yr. Because sufficient UREX+ capacity is provided to allow the system to eliminate "accessible" inventories by 2100, in the no-backup variation, VISION builds a large number of ABRs to work through the inventories so that the simulation ends in 2100 with 160 GWe instead of 120 GWe in the GNEP case (figure 5-7). If backup is implemented, the system builds ABRs at a more modest rate and reaches 120 GWe in 2100 (figure 5-7).

[11] This result is based on the ABR decide-to-build algorithm that considers the TRU needed for life-time fuel supply.

Figure 5-9 shows the same information as figure 5-7, but graphed as fraction of the total fleet.

Figure 5-9. Fast reactor capacity

For the GNEP case of UOX-ABR, the ABR fraction of the fleet climbs to ~18%, whereas the static equilibrium fraction (at CR=0.25) is 27%. With non-zero nuclear growth, the fraction of ABRs in the fleet never reaches static equilibrium because of the various time lags in the system. Instead, the system reaches a dynamic equilibrium that is lower than the static equilibrium. As the graph shows, the dynamic equilibrium for 2.25% growth is actually below 18% and the percent ABRs is declining toward the end of the simulation as excess LWR SNF inventories supporting the ABRs are worked off.

The construction of ABRs is inhibited by TRU availability. In these calculations, the TRU availability stems from the output of LWRs a minimum of 7 years earlier, as the TRU in the discharged LWR fuel must cool before transport, then be chemically separated, then be made into fuel. The ratio of ABRs in year X to the LWR+ABR fleet in year X-7 is closer to static equilibrium, about 20% at 2.25%/yr growth rate versus the static equilibrium value of 27%. This impact becomes more significant the faster nuclear growth; i.e., the system moves further from equilibrium the higher the growth rate. Another key difference is that the startup ABR core composition differs from the equilibrium core composition.

With 1-pass MOX or IMF added to the system in a serial fashion (TRU does not go to ABRs until passing through MOX or IMF), the static equilibrium ABR fraction is 19% instead of 27% for the UOX-to-ABR GNEP case. But, figure 5-9 shows that in the dynamic calculations, with MOX or IMF added to the system, the ABR fraction drops from ~18% (GNEP) to 5-9% (with MOX/IMF mixed recycling). In addition to all the other time lags, the MOX/IMF-to-ABR "mixed" cases has the additional time lags associated with sending TRU to MOX/IMF, waiting for the used fuel to cool, separating it, and only then using the TRU in ABRs. In these

calculations, the TRU availability for ABRs stems from the output of LWRs at least 18 years earlier.

The VISION model currently lacks the ability to run MOX/IMF and ABRs in a parallel fashion, i.e., allocating the TRU supply from used UOX fuel somehow between those two reactors. Used MOX/IMF fuel would then go to ABRs; used ABR fuel stays with ABRs.

5.6 Waste Management

Figure 5-10 shows the accessible inventory of used fuel. This includes the legacy used fuel in 2000 and used fuel in dry storage, whether at-reactor or a centralized storage location. Each curve starts with the 43 kt of legacy fuel in 2000, then grows due to discharge from the LWR fleet, turns over as 63 kt is shipped to the repository and recycling is deployed, and is then maintained at low levels as specified in section 5.2.

Figure 5-10. Accessible used fuel as function of time

5.7 Proliferation Resistance

Figure 5-11 shows an indicator of weapon "attractiveness" or "quality" – the ratio of Pu239/Pu-total. The graph shows the average ratios for the entire system. This metric does not show a major degradation of the average composition of the system. (Pu239/TRU behaves the same.) The IMF cases show more and faster degradation than the other cases. Certain parts of the system, however, do show important degradation as measured by other metrics, most importantly neutron and gamma emission.

Figure 5-11. Ratio of Pu239/Pu-total in the system

5.8 Energy Recovery

Unless fast reactors are used with conversion ratio very close (>0.97) or greater than 1, the energy recovery does not change much relative to the once-through case. As noted in section 5.4, in dynamic analyses, the number of fast reactors is always lower than equilibrium. Thus, the improvement in energy recovery potentially afforded by any fast reactor, relative to thermal reactors, is reduced relative to the equilibrium calculations discussed in section 4.3. Integrated over this century, none of the cases studied (at CR=0.25) show uranium improvement factors greater than 1.1, i.e., 10% improvement. Recycling some of the transuranics in thermal reactors reduces the improvement relative to fast reactors. None of the recycle cases studied do worse than once-through.

5.9 Economics and Safety

Figure 5-12 shows the mass in UREX+ separations, relevant to economics and safety. Through mid-century the amount in UREX+ separation does not vary among cases and is constrained by the UREX+ build rate requested in figure 5-6; all available separation capacity is in use. After 2060, some of the cases show temporary reduction in separation mass, denoting the presence of some unused UREX+ capacity. Coordinating the deployment of all parts of these systems is complex. Future analyses would benefit from refinement in the decide-to-build algorithms presented in section 5.2.

Note the mass shown in Figure 5-12 reflects how much material is in the plant, not the annual rate. VISION assumes two timesteps (six months) to move spent fuel through the plant. Thus when comparing the requested capacity (Figure 5-6) to that actually used, these mass rates

should be doubled to get annual rates. Remaining differences are due to other system constraints, such as LWR spent fuel availability.

Figure 5-12. Mass in UREX+ separations

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6. CONCLUSIONS

Recycling of used nuclear fuel transuranics in LWRs has several potential benefits. Fuel cycle strategies utilizing recycling in LWRs can be developed with or without concurrent recycling in fast reactors. The recycling in LWRs can be for a single pass or done repeatedly. In general, there are several possible roles for LWR recycling, as follows:

1. **Stop-gap recycling** – One recycle pass in thermal reactors followed by subsequent recycle in fast reactors.
2. **Mixed recycling** – Recycling for many decades with a symbiotic mix of thermal and fast reactors.
3. **Backup recycling** – Recycling in thermal reactors if economic or acceptance problems develop with fast reactor recycling.
4. **Pure thermal** - Thermal reactors as the only planned mechanism to recycle used fuel.

The first three roles are potential risk management options for the GNEP approach of using only fast reactors to recycle used nuclear fuel. The last role was considered in the AFCI, but is not compatible with the GNEP strategy.

Table 6-1 summarizes the implications associated with recycling none, one, or more of the transuranic elements.

Table 6-1. Implications of Recycling None, One, or More Transuranic Elements

Which elements recycled?	Geologic repository benefits based on improvement in heat load to the repository	Radiation field implications	Readiness in …	
			Thermal reactors (LWR)	Fast reactors (sodium-cooled)
No recycle	None (U.S. status quo)	Hands-on fabrication	Widespread commercial experience	N/A
Recycle Pu	Low relative to once-through unless Am recycled later	Glovebox fabrication required	Commercial experience in some countries	Significant test reactor experience
Recycle Np-Pu		Glovebox fabrication required	Pu-type fuels would be modified to include Np (only a small amount of Np is involved).	
Recycle Np-Pu-Am	High (~100x in fast, ~10x in thermal) if eventually consumed	High gamma emission; remote fabrication	Pu-type fuels would be modified to include Np and Am, or development of targets for Np and Am would be required. A difficult separation of Am from Cm would be required.	
Recycle all TRU	High (~100x in fast, lower in thermal) if eventually consumed	High gamma and high neutron emission; remote fabrication; weapon physics impaired by neutron emissions	Pu-type fuels would be modified to contain all TRU, or development of targets for Np, Am, and possibly Cm would be required	

This report is not intended to be a complete comparison of IMF versus MOX as vehicles for recycle in thermal reactors. The two cases were analyzed to identify the range of possible thermal recycle performance.

The net consumption of unwanted TRU isotopes in the IMF approach is relatively fast because there is no uranium-238 as a source of new TRU isotopes. The segregation of Pu and other transuranic isotopes into IMF pins reduces the competition for neutrons that moderate in the vicinity of those pins, hence the faster net consumption of TRU with IMF versus MOX. The IMF advantage versus MOX is reduced but not eliminated in heterogeneous IMF assemblies with blending new fissile material each recycle. The consumption of unwanted TRU isotopes in the mixed oxide (MOX) approach is inefficient. U235 and U238 compete with the TRU isotopes as neutrons moderate.

The matrix material in MOX (uranium) provides a material that is stable in reactors but also recyclable. In contrast, eliminating uranium from IMF means that no new transuranic elements can be created, but it also means that the chemical matrix of the fuel must be based on something other than uranium. This requires finding an alternative matrix material that, like uranium, is sufficiently easy to chemically separate but sufficiently stable to give good fuel performance. This search has proven difficult.

There is considerably more experience with MOX-Pu than IMF-Pu. However, MOX-TRU and IMF-TRU have both been judged to be at the same low level of technology readiness [DOE2006] because both technologies involve fabrication with americium and curium, which is a substantially different challenge than MOX-Pu.

The improvement in uranium ore utilization relative to the current once-through fuel cycle is limited to 20% improvement in thermal reactors or low conversion fast reactors, whereas fast breeder reactors can achieve a factor of 100 improvement.

6.1 Pure Thermal Recycling

Thermal recycle does not eliminate the eventual need for fast reactors, a need driven by achieving the highest potential repository benefits and eventually extending uranium supplies by shifting fast reactors to the breeder mode.

One recycle pass in thermal reactors does not meet advanced fuel cycle objectives.

Recycling in thermal reactors is sustainable provided two constraints are addressed. First, thermal reactors preferentially consume fissile isotopes versus fertile; thus, continued recycling requires a continuing source of fissile material. The most practical source of new fissile material is enriched uranium or new used LWR fuel; either approach reduces the benefit of recycling the original material because of dilution with new material (on a per GWe-year of used fuel basis).

The other constraint is that thermal reactor physics (Appendix A) inherently promotes faster accumulation and higher equilibrium inventories of higher transuranic elements. All of the transuranic elements are radioactive, all generate heat, all emit gamma radiation. Thus, heat and

gamma emission, by themselves may not be insurmountable as the inventory of transuranic elements shifts to higher elements. The heat and gamma emission appear to increase only an order of magnitude or so higher in thermal reactors than in fast reactors, over repeated recycles. Heat and gamma emission are not discriminators between thermal and fast recycle.

In general, however, the higher transuranic elements are much more prone (orders of magnitude) to emit neutrons. The greater shift to higher transuranic elements in thermal reactors than in fast reactors can therefore lead to higher neutron emission in thermal reactors than in fast reactors. The thermal-to-fast penalty depends on many factors, but may be several orders of magnitude. Five approaches to this challenge have been proposed, as follows:

1. Only recycle in fast reactors.

2. Recycle the higher transuranic elements (curium and above) in fast reactors, and the lower transuranic elements in thermal reactors. This requires a difficult separation of americium from curium.

3. Dispose of the curium (and above). This recycle approach is sustainable with additional of fresh fissile material. Heat, gamma, and neutron emission are an order of magnitude higher than recycling Pu alone. The combination of fresh fissile material and Cm disposal limits the equilibrium reduction in heat load to the repository to ~10x (with IMF) after many recycles, compared to ~100x for pure fast systems. And, this requires more separation steps than recycle of all the transuranic elements together.

4. Store the curium (and above) to let key isotopes delay.[Collins2004, Collins2007] Storage for several decades allows Cm244 (18.1 year halflife), Cf250 (13.1 year), and Cf252 (2.638 year) to substantially decay. These isotopes are responsible for 90% to 99% of the neutron emission when all transuranics are recycled in thermal reactors. This decay storage can be implemented at various points in the fuel cycle, between reactor and separation, between separation and fabrication, and between fabrication and use of the new fuel in reactors. This can be implemented with all the transuranic elements together, e.g., if done between reactor and chemical separation, or combined with separating NpPu versus Am, Cm, and above, thus allowing most of the transuranic elements to be recycled quickly while storing curium and above. These storage concepts would require relatively expensive facilities to store the highly radioactive and neutron-emitting material. If these elements are neither disposed nor consumed in fast reactors, the recycled transuranic fuel material becomes intensely radioactive after a few recycles. If Cm/Bk/Cf are handled separately from NpPuAm, then a difficult and relatively unproven chemical separation is required (Am vs Cm). Still, storage approaches appear capable of reducing the neutron emission by a few orders of magnitude. Additional analyses are warranted to determine equilibrium heat-load benefits for geologic disposal; it should be between ~10x (IMF, with Cm disposal) and ~100x (fast reactors, without Cm disposal).

5. Accept the penalties of accumulating higher transuranic elements in thermal reactors. Both thermal and fast reactors have minor waste management benefits if only Pu is recycled (Appendix B). Both thermal and fast reactors have higher heat, gamma, and

neutron emission when all transuranic elements are recycled than if only Pu is recycled (Appendix A, Table 4-2). In thermal reactors, the penalty for recycling all transuranics versus only Pu is 10-40x for heat and gamma emission, but 10,000x to 100,000x for neutron emission. These high energy neutrons are difficult to shield. Additional analyses would be warranted before serious consideration of such an approach. The penalty in fast reactors of recycling all transuranics will be lower than thermal reactors, especially for fast breeder reactors, but needs better quantification. Additional analyses are warranted to determine equilibrium heat-load benefits for geologic disposal; it should be between ~10x (IMF, with Cm disposal) and ~100x (fast reactors, without Cm disposal).

The first and second of the above approaches involve fast reactors and are considered in the next subsection. The third avoids Cm/Bk/Cf accumulation in recycled TRU material but does not meet long-term fuel cycle waste management objectives due to accumulation of disposed higher transuranics and blending in additional fissile material to sustain recycle. The fourth approach mitigates the Cm-disposal problem and the Cm-accumulation problem but still requires blending in additional fissile material to sustain recycle. The fifth avoids the waste management repository performance problem of accumulated Cm disposal, but has high Cm (and above) accumulation in recycled TRU material.

Said another way, the equilibrium reduction in heat load to a geologic repository can be ~100x if all transuranics are recycled and no blending of additional transuranic material must be done each cycle. This combination can only occur with fast reactors in the system. All thermal systems require blending additional transuranic material and thus cannot reach as high a performance.

It is emphasized that recycling all the transuranic elements will increase neutron emission substantially compared with current experience with nuclear fuels. The analyses presented here indicate that that increase will be highest for pure thermal recycle, intermediate for fleets involving thermal reactors and fast burner reactors, and least for fast breeder reactors. The issues associated with neutron-emitting fuels have been identified,[Briggs2002, NEA2005] and the magnitude of the neutron emission clarified in this report. More work is required on how best to address those issues.

From the standpoint of destruction of unwanted TRU isotopes, thermal reactors are less neutron efficient than fast reactors. Most of the unwanted TRU isotopes in used LWR fuel are fertile, not fissile, because the fissile ones have a high probability of fissioning before the LWR fuel is discharged. Thus, the major pathway for further reduction of unwanted TRU isotopes in used LWR fuel is neutron capture, which often leads to a new fissile isotope. A second neutron can then fission that isotope. In contrast, fast reactors have higher probability of fissioning fertile isotopes so that a single neutron can eliminate an unwanted TRU isotope.

6.1 Thermal Recycling in Conjunction with Fast Recycling

Thermal recycle provides several potential benefits when used as **stop-gap, mixed,** or **backup** recycling in conjunction with recycling in fast reactors.

Stop-gap recycling – One recycle pass in thermal reactors followed by subsequent recycle in fast reactors. This accommodates potential delay of fast reactors by one or two decades, while still starting sustainable recycling of used fuel. Thereafter, the one recycle pass in thermal reactors would be phased out. Recycling can start to consume transuranic material (far faster with IMF than MOX). The rate of consumption is controllable by the amount of IMF or MOX deployed. Implementing IMF approaches require solving difficult separation and fabrication issues, which are beyond the scope of this report.

Mixed recycling – Recycling for many decades with a symbiotic mix of thermal and fast reactors. This would reduce the fraction of fast reactors required. It also provides "buffer" recycling capability where changes in transuranic supply from LWRs could be accommodated by changing the amount of recycling in thermal reactors, leaving the fast reactor portion of the fleet unaffected.

For example, at fast reactor conversion ratio of 0.25, the static equilibrium fraction of fast reactors would drop from 27% without thermal recycling to 19% with thermal recycling. With time-dependent analyses, the fraction of fast reactors is always lower than the static equilibrium because of various time lags in the system; the new number depends on many factors such as the growth rate of nuclear energy. At a nuclear power growth rate of 2.25%/year, the fraction of fast reactors without thermal recycling drops from ~27% to ~16%. With thermal recycling in a serial fashion – TRU goes from LWR-UOX to LWR-MOX/IMF to ABR - the fraction of fast reactors decreases from ~18% to 5-9% at 2.25%/yr growth rate, in part because of two decade time lags between LWR-UOX discharge and ABR insertion.

Backup recycling – Recycling in thermal reactors if economic or acceptance problems develop with fast reactor recycling. This mitigates accumulation of transuranic stockpiles and avoids the economic penalty of stopping the separation plants that are processing used LWR fuel. The backup recycling could be continued for as long as needed, resuming recycle in fast reactors when possible.

Note that the separation plant processing used LWR fuel is assumed to start before fast reactors to provide the fast reactors with fuel. Thus, if economic or acceptance problems develop later with the fast reactor component of the program, the choice is among terminating the separation plant; accept the accumulation of separated transuranic material; or recycle the material in thermal reactors. The backup recycling could be continued for several decades.

6.3 General Observations

The approach of using only fast reactors to recycle separated transuranics requires coordination among the construction of capability for chemical separation of used LWR fuel, fabrication of new recycled fuel, and fast reactors. Adding some thermal recycling to this approach is a way to provide more latitude in the timing of when new reactors come on line.

Any thermal recycle provides a buffer in case the number of LWRs supplying TRU to the system is higher or lower than planned.

Initiation of any recycle may also allow reclassification of some waste liabilities into energy assets, e.g., show separated TRU on the asset side of the ledger instead of the waste side.

There are additional potential benefits for specific technology options. Of all options studied, repository benefits may accrue the fastest (as measured by the number of recycle passes) by one to three IMF cycles followed by fast reactors; this appears faster than fast reactors alone and more sustainable than IMF alone. If too many IMF cycles are done, the problem of accumulation of high transuranic isotopes degrades performance.

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Appendix A. Differences between Thermal and Fast Reactors

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A.1 The Two Types of Reactors

There are two basic types of nuclear reactors – thermal and fast. Their different properties lead to significant differences in fuel cycle possibilities. The differences arise from the energy of neutrons within the reactors.

- **Thermal reactors** – most neutron reactions occur via neutrons having relatively low average energy.
- **Fast reactors** – most neutron reactions occur via neutrons having relatively higher average energy.

All fission neutrons are born at high energy (~1 MeV). The difference of the reactor types is that the presence of moderating materials gives thermal reactors a population of low energy neutrons, of similar magnitude to its population of high energy neutrons. Because reaction rates are higher at lower energies, most of the nuclear reactions therefore occur at these low energies. Fast reactors primarily have high energy neutrons.

The rate of reactions of neutrons with materials depends on the neutron energy. There are two basic types of reactions – capture and fission.

- When a material **captures** a neutron, the chemical element stays the same, but the isotope of the element then has one additional neutron, e.g., Co59 (stable) captures a neutron and turns into Co60 (5.27-year halflife). This often makes the material radioactive. It generally wastes the neutron because little or no net energy is released. Sometimes the neutron subsequently decays into a proton and an electron, resulting in a heavier element. This is how transuranics are created from uranium.
- In fission reactions, the neutron causes the material to **fission** (split) into two or more fission products, typically two or three new neutrons, and substantial energy release. The fission products are different chemical elements than the starting material. Materials that will fission, called "fissionable," are potential fuels for nuclear power plants.

The chance that a neutron is captured by the material is generally higher for lower energy neutrons. Thus, thermal reactors generally waste more neutrons than fast reactors.

The chance that a neutron causes a fission reaction is more complex. It turns out that fissionable isotopes divide into two types, which this Appendix first discusses qualitatively and then quantitatively.

- **Fissile isotopes** are readily fissioned by thermal neutrons; they will also fission by fast neutrons.
- **Fertile isotopes** are not readily fissioned by thermal neutrons; they will fission to some degree by fast neutrons.

Thus, fissile isotopes can sustain the fission reaction in thermal reactors, but fertile isotopes cannot. Both fissile and fertile isotopes contribute to sustaining the fission reaction in fast reactors.

The only fissile isotope that occurs significantly in nature is uranium-235, which is only 0.7% of natural uranium. The major fertile isotopes that occur in nature are uranium-238 (99.3% of natural uranium) and thorium-232 (100% of natural thorium).

When fertile isotopes capture a neutron, they generally transmute into a fissile isotope. Thus, neutron capture by a fertile isotope does not waste the neutron in the same sense that a non-fissionable material does.

Returning to the two types of nuclear reactors, the above discussion of physics may clarify the difference between thermal and fast.

- In **thermal reactors**, the primary fuel from nature is fissile uranium-235, which fissions readily. Fertile uranium-238 will capture a neutron, becoming fissile plutonium-239, which also fissions readily. However, many non-fuel materials will also capture (and waste) neutrons.
  - Thermal reactors are relatively inefficient in using uranium ore.
  - Thermal reactors can readily fission only some of the transuranic isotopes (the fissile ones).
  - Thermal reactors can be designed with a wide variety of non-fuel materials, including water as a coolant.
- In **fast reactors**, both uranium-235 and uranium-238 can be considered fuel. The rate of fission is lower per neutron, but the rate of non-fuel capture is also lower. Thus, to have the same energy output, relatively more neutrons must move through the reactor. This limits the amount of materials that reduce the energies of neutrons, such as water and carbon, must be used in small amounts. That is why fast reactors are not water cooled, instead they use coolants such as sodium that do not moderate neutrons so readily.
  - Fast reactors are relatively efficient in using uranium ore.
  - Fast reactors can fission all of the transuranic isotopes.

World-wide, essentially all commercial nuclear power plants today are thermal reactors. The French, Japanese, and Russians have operating fast reactors. World-wide, it is recognized that if uranium supplies because a serious constraint, there will be a shift from thermal to fast reactors.

A.2 Differences in Energy Recovery

About 1.6% of the hypothetical energy content in used LWR fuel comprises fissile isotopes such as uranium-235 and plutonium-239. There is ~500 tonnes of plutonium in the used fuel already accumulated in the U.S. This has the energy equivalence of 6.6 billion barrels of oil, which is half of the estimated resources in Prudhoe Bay, Alaska.

The other 98% of the hypothetical energy content in used LWR fuel are fertile isotopes such as uranium-238 and americium-241. Use of the energy from both fissile and fertile parts of the existing used fuel (~50,000 tonnes) would be twice the energy content of Saudi Arabian oil reserves.

Use of the energy from existing depleted uranium (~500,000 tonnes) would be equivalent to about six times world oil supplies. Fast breeder reactors are required to access this resource. The world's uranium ore resources are many times this number.

A.3 Differences in Waste Management

Section A.2 focused on energy recovery. The two types of reactors also differ in their ability to destroy specific transuranic isotopes that are important to waste management. There have been competing claims on the ability of thermal versus fast reactors to destroy specific troublesome isotopes; the rest of this Appendix attempts to clarify, at the penalty of diving into reactor physics.

Most of the isotopes important to waste management are fertile, such as neptunium-237, plutonium-238, plutonium-240, and americium-241. One reason is that many of the fissile isotopes that would otherwise be present in used fuel are instead consumed *in-situ* in the LWR.

Thermal reactors can destroy troublesome fertile isotopes by neutron capture, which often turns the fertile isotope into a fissile isotope. Ultimate destruction of the fertile isotope therefore requires at least two neutrons – one to transmute the fertile isotope into a fissile isotope, one to fission the fissile isotope.

Relative to thermal reactors, fast reactors more readily fission the fertile isotopes, but are often less able to destroy the fertile isotopes by neutron capture. Ultimate destruction of the fertile isotopes often only requires one neutron – to fission the fertile isotope. Thus, fast reactors are more efficient in use of neutrons to destroy troublesome fertile transuranic isotopes. Both thermal and fast reactors often only require one neutron to destroy troublesome fissile transuranic isotopes, by fission.

The actual situation, of course, is more complicated than the above qualitative description suggests. A way of measuring neutron efficiency is to calculate "D-factors," which are the number of neutrons consumed or produced per an initial neutron captured by an isotope. The calculation includes the various daughters of the original isotope.[Hill2004] A value of zero means that the isotope is a net "wash." A negative number means the isotope is a net producer of neutrons in that particular reactor and neutron spectrum. A positive number means the isotope is

a net sink for neutrons. Table A-1 lists D-factors for key isotopes for illustrative thermal/MOX reactor and sodium fast reactor.[Hill2004]

Table A-1. D-factors (Neutron Sink or Source) for Thermal and Fast Reactors[Hill2004]

Reactor type	Thermal			Fast		
Coolant	Light water			Sodium		
Fuel	MOX			Oxide	Oxide	Metal
Design (pin pitch for LWR cases)	r = 1.4	r = 2	r = 4	Superphenix	Newer design	
Neutron flux (neutrons-cm^2/sec)	10^{14}			10^{15}		
U235 (fissile)	-0.31	-0.38	-0.55	-0.86	-0.95	-1.04
U238 (fertile)	0.10	0.07	-0.01	-0.62	-0.79	-0.90
Np237 (fertile)	0.91	0.93	0.96	-0.56	-0.73	-0.88
Pu238 (fertile)	0.01	0.02	0.04	-1.33	-1.41	-1.50
Pu239 (fissile)	-0.60	-0.64	-0.73	-1.46	-1.61	-1.71
Pu240 (fertile)	0.65	0.56	0.38	-0.91	-1.13	-1.27
Pu241 (fissile)	-0.26	-0.37	-0.58	-1.21	-1.33	-1.39
Pu242 (fertile)	1.27	1.22	1.13	-0.48	-0.92	-1.13
Am241 (fertile)	0.92	0.93	0.95	-0.54	-0.77	-0.91
Am242m (fissile)	-1.55	-1.56	-1.56	-1.87	-2.10	-2.16
Am243 (fertile)	0.44	0.36	0.25	-0.65	-1.01	-1.15
Cm242 (fertile)	0.00	0.01	0.03	-1.34	-1.41	-1.51
Cm244 (fertile)	-0.51	-0.60	-0.71	-1.44	-1.64	-1.71
Cm245 (fissile)	-2.46	-2.46	-2.44	-2.69	-2.74	-2.77

The table illustrates several points. First, the exact neutron balance depends on design.

Next, consider fissile versus fertile isotopes. The general pattern of which isotopes are fissile and which are fertile is given in Table A-2.

Table A-2. Pattern of Fissile versus Fertile Isotopes

	Fissile	Fertile
Even numbered element (U, Pu, Cm, Cf)	Odd numbered isotopes, e.g., U235, Pu239, Pu241	Even numbered isotopes, e.g., U238, Pu238, Pu240, Pu242, Cm244
Odd numbered element (Np, Am, Bk)	Even numbered isotopes, e.g., Am242 and Am242m	Odd numbered isotopes, e.g., Np237, Am241, Am243

Table A-1 shows that fissile isotopes are always net neutron providers, in both thermal and fast reactors. Fertile isotopes are always net neutron providers in the fast reactor cases, but generally net neutron sinks in the thermal reactors. There are two exceptions.

- First, in this methodology, U238 can be a slight neutron provider. This occurs when the isotope is in a very soft (lower energy) spectrum and fissile Pu239 production from the U238 is maximized.
- Second, Cm244 is a net neutron provider. One reason is that Cm244 can spontaneously fission, emitting a neutron.

Among the fissile isotopes in Table A-2, the average neutron gain is about 0.6 neutrons higher in fast reactors than thermal reactors. Among fertile isotopes, the average neutron gain is about 1.5

neutrons higher in fast than thermal. Fast reactors are indeed more efficient in using neutrons to produce fission.

However, the relative **rate** of destruction of troublesome isotopes involves more factors than neutron **efficiency**.

Figure A-1 shows five types of nuclear reactions.

1. Neutron capture, typically producing a gamma particle. This adds 1 to the number of neutrons in the isotope.
2. Alpha decay, subtracting 2 protons and 2 neutrons.
3. Beta decay, changing a proton into a neutron, or vice versa.
4. Spontaneous fission, isotope disintegrates and emits neutrons.
5. Internal decay, changing from meta state to ground state, e.g., Am242m to Am242.

In a reactor, there is another reaction – neutron-induced fission. This is not shown in figure A-1 because it would apply to all of the isotopes shown. Fission of any isotope in the diagram leads to fission products, which are outside the diagram. (Also, other less frequent reactions are not shown.)

The probability of each capture and fission reaction is denoted by its "cross section" times the number of neutrons present. The cross section is a function of the isotope, reaction, and energy of neutrons present. The probability of alpha, beta, and spontaneous neutron decay is given by the decay constant of that particular isotope. When fuel is removed from a reactor, the capture and fission stop. Decay continues.

Thus, calculating the net production or destruction of a given isotope requires consideration of all the pathways leading to and from that isotope.

Although lists of cross sections are not sufficient to determine the destruction/production rate of a given isotope, examination of cross sections help clarify trends. Table A-3 gives average capture and fission cross sections.

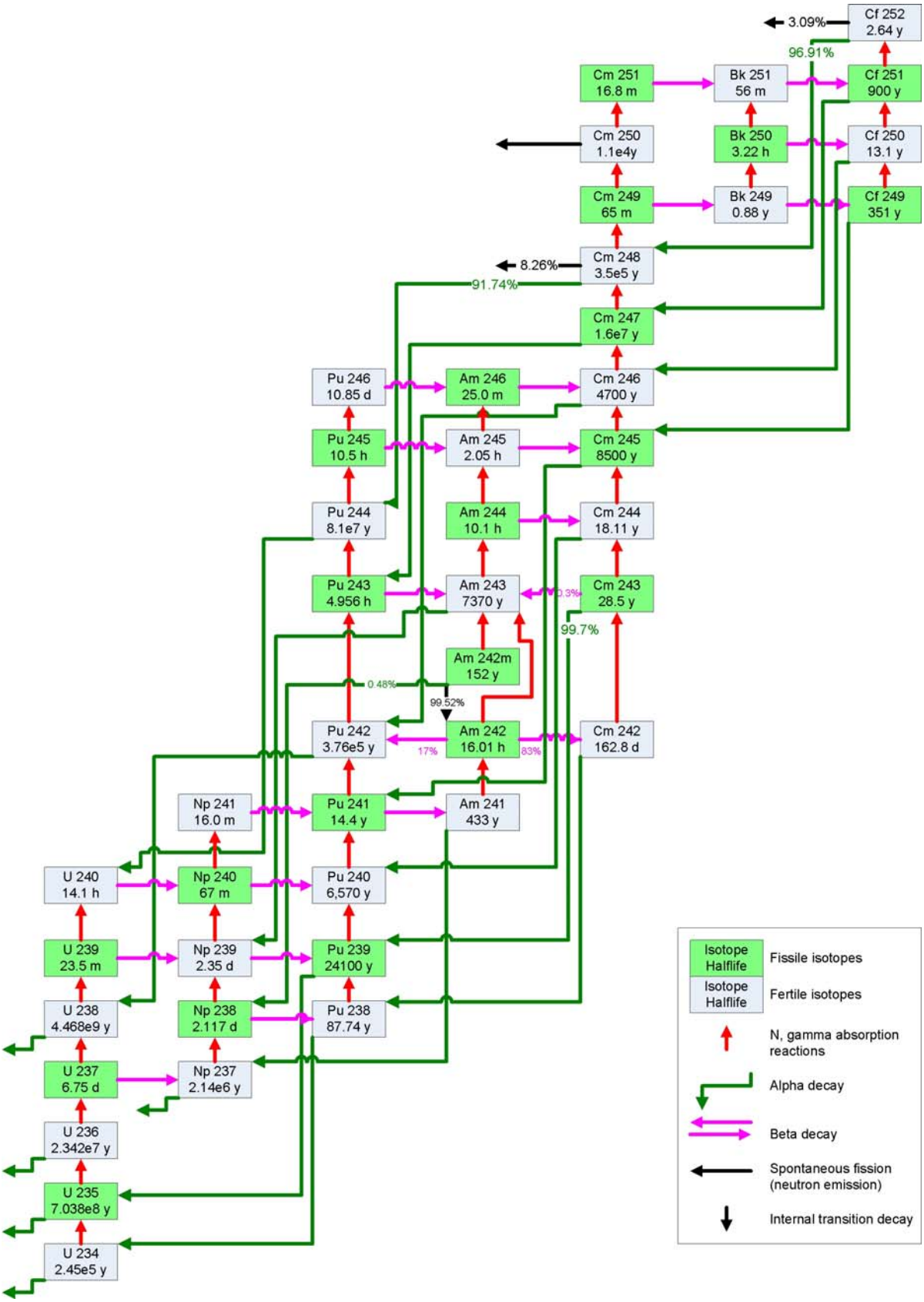

Figure A-1. Schematic of reactions leading to troublesome isotopes

Table A-3. Average Cross Sections from the ORIGEN2.2 Database

	Average 1-group cross section in units of "barns" – higher numbers denote higher chance of the reaction occurring			
	Illustrative fast reactor (sodium cooled)		Illustrative thermal reactor (Pressurized Water Reactor)	
	Capture ($\sigma_{c,fast}$)	Fission ($\sigma_{f,fast}$)	Capture ($\sigma_{c,thermal}$)	Fission ($\sigma_{f,thermal}$)
Fissile isotopes	0.3	1.8	39.4	125.2
Fertile isotopes	0.6	0.4	60.6	1.0

Consider the average number of neutrons produced when an isotope fissions (ν) times the ratio of fission/capture, ($\nu\ \sigma_f/\sigma_c$). This average number (ν) is typically between 2 and 3.

If this ratio ($\nu\ \sigma_f/\sigma_c$) is greater than one, there are more neutrons produced from fission ($\nu\ \sigma_f$) on average than captured (σ_c). Thus, there is a chance the isotope is useful as a nuclear fuel. Whether it is actually a practical fuel depends on how many neutrons leak out of the reactor and how many are captured by non-fuel materials. If this ratio ($\nu\ \sigma_f/\sigma_c$) is less than one, the isotope cannot be used directly as a nuclear fuel.

In fast reactors, the values in Table A-3 show that the ratio ($\nu\ \sigma_{f,fast}/\sigma_{c,fast}$) is roughly 15 for fissile (2.5 x 1.8/0.3) and 1.7 for fertile (2.5 x 0.4/0.6). Thus, both fissile and fertile isotopes are potentially useful as fuel, but the fissile isotopes are more valuable. In thermal reactors, that ratio ($\nu\ \sigma_{f,thermal}/\sigma_{c,thermal}$) is 8 for fissile and 0.04 for fertile. Thus, fissile isotopes are usable as fuel; fertile isotopes are not.

For fissile isotopes, the fission cross section in thermal reactors ($\sigma_{f,thermal}$) is 70x higher than in fast reactors. Thus, to produce the same amount of power from fission, a fast reactor needs 10 to 100 more neutrons active in the reactor (the neutron flux), depending on which isotopes dominate the overall fission rate. For example, the ratio of fission cross section for U235 in a thermal reactor to fission cross section for Pu239 in a fast reactor is 22 (= 41/1.85). Table A-1 showed a typical comparison, in which the fast reactor has 10 times more neutrons than the thermal reactor.

The combination of fission+capture ($\sigma_f + \sigma_c$) is a measure of the probability of destroying an isotope. For fertile isotopes, which dominate waste management issues, consider the ratio of fission+capture in fast reactors to fssion+capture in thermal reactors, times 10, or

$$(\sigma_{f,fast} + \sigma_{c,fast})/(\sigma_{f,thermal} + \sigma_{c,thermal}) \times 10.$$

This ratio is about 0.2, meaning that, on average, the destruction rate for a fertile isotope is higher in a thermal reactor than in a fast reactor. However, in a thermal reactor, the average fertile isotope would have less than 2% chance of fission (1/(1+60.6)) but have 40% chance of fission in the fast reactor (0.4/(0.4+0.6)). So, in a thermal reactor, there is more chance that the average troublesome fertile isotope has merely been exchanged for another isotope (98% versus 60%).

To further complicate the comparison, the new isotope is generally fissile. So, a complete analysis then has to follow whether that new isotope decays (beta decay makes fertile, alpha decay keeps it fissile), fissions, or captures yet another neutron (making it fertile again).

This exercise shows the following:

- It is impossible merely from knowing cross sections to know the best way to destroy a troublesome isotope.
- To produce the most troublesome isotopes from the original uranium isotopes, it is generally necessary for many reactions to occur, e.g., at least 10 neutrons must be captured starting with U238 to produce Cm248. So, the accumulation of the high neutron emitters Cm244, Cm248, Cm250, Cf252 does not happen quickly.
- Fission energy generation
  - Fast reactors are more efficient in using neutrons to produce energy via fission.
  - However, per neutron, fast reactors have lower fission reaction probability (cross sections) than thermal reactors, thus, to have the same power level, fast reactors have more active neutrons than thermal reactors.[12]
  - Fissile isotopes are usable as fuel in both thermal and fast reactors.
  - Fertile isotopes are usable as fuel in fast reactors (barely), not in thermal reactors.
- Fertile isotope destruction
  - Fast reactors are more efficient in using neutrons to destroy fertile isotopes.
  - When a thermal reactor destroys a particular fertile isotope, the immediate result is most likely (98%) to be a fissile isotope, rather than fission (2%). If this isotope captures another neutron before it decays or fissions, the original isotope has moved up two neutrons toward the neutron emitting Cm and Cf.
  - When a fast reactor destroys a particular fertile isotope, it may have either fissioned (40%) or transmuted into a fissile isotope (60%). Thus, the accumulation of yet higher isotopes (leading to Cm, Bk, and Cf) is generally less in fast reactors than thermal reactors.

[12] Thus, typically there are more neutrons leaking out of the fast reactor core than a thermal reactor core. In a breeder fast reactor a zone high in fertile uranium-238 is used to capture the leaking neutrons, thereby producing fissile plutonium-239.

Appendix B. Which Elements Should be Recycled for a Comprehensive Fuel Cycle

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Which chemical elements should be recovered to achieve various potential objectives? Section B.1 explains that the original focus of recycling was energy recovery, which led to separation of plutonium and uranium. Section B.2 shows how consideration of other objectives such as waste management necessitates separation and management of other elements.

B.1 The Original Focus of Recycling was Energy Recovery

Figure B-1 shows that about 95% of used nuclear fuel mass is useful material, uranium (94%) and the transuranic elements of neptunium, plutonium, americium, and curium (1%). The other 5% of used fuel comprises fission products, the "ash" resulting from the nuclear fission reaction; these contain no recoverable energy.

Figure B-2 shows that uranium and plutonium constitute 99.8% of the energy content in used fuel. This is why current nuclear fuel recycling efforts in France, United Kingdom, Japan, and Russia use separation technologies such as PUREX that only separate uranium and plutonium. That is all that is needed for energy recovery

Figure B-1. Composition of used nuclear fuel at 50 MW-day/kg burnup

These facts have been known for decades; recycling used fuel for its energy content only requires recovery of uranium and plutonium. The plutonium is mostly fissile and can be readily recycled in thermal reactors; the uranium is mostly fertile and best recycled in fast reactors. Appendix A describes the difference between thermal and fast reactors and the difference between fissile and fertile isotopes.

Recycling for energy recovery is currently done in France, United Kingdom, Russia, and starting in Japan. Nonetheless, the urgency for full-scale energy recovery depends on projections for the need and supply of uranium. One of the reasons the U.S. decided three decades ago to abandon reprocessing of nuclear fuel was the assessment that uranium supplies were plentiful and uranium need was expected to be modest.

Figure B-2. Energy content of used nuclear fuel at 50 MW-day/kg burnup

B.2 New Focus of Recycling adds Waste Management

Trends in other industries suggest that recycling will continue to grow in acceptance, with better economics, whereas waste disposal will continue to drop in acceptance, with worse economic and social costs. The U.S. census bureau statistics indicate that about a quarter of municipal waste is now burned for energy and another quarter is recovered for reuse. Recycling can and should address constraints other than energy recovery, in particular waste management. What can recycling of used nuclear fuel do for waste management?

To answer this question, look at the composition of used nuclear fuel from other perspectives than energy recovery. Like other wastes, used nuclear fuel is toxic, primarily because of radioactive isotopes. Internationally, a common way to describe the hazard of used fuel is radiotoxicity, which is the inventory of radioisotopes divided by their relative hazard to humans.

Figure B-3 shows the radiotoxicity of used nuclear fuel relative to the uranium ore that started the process.[13] It remains more radiotoxic than uranium ore for about a million years.

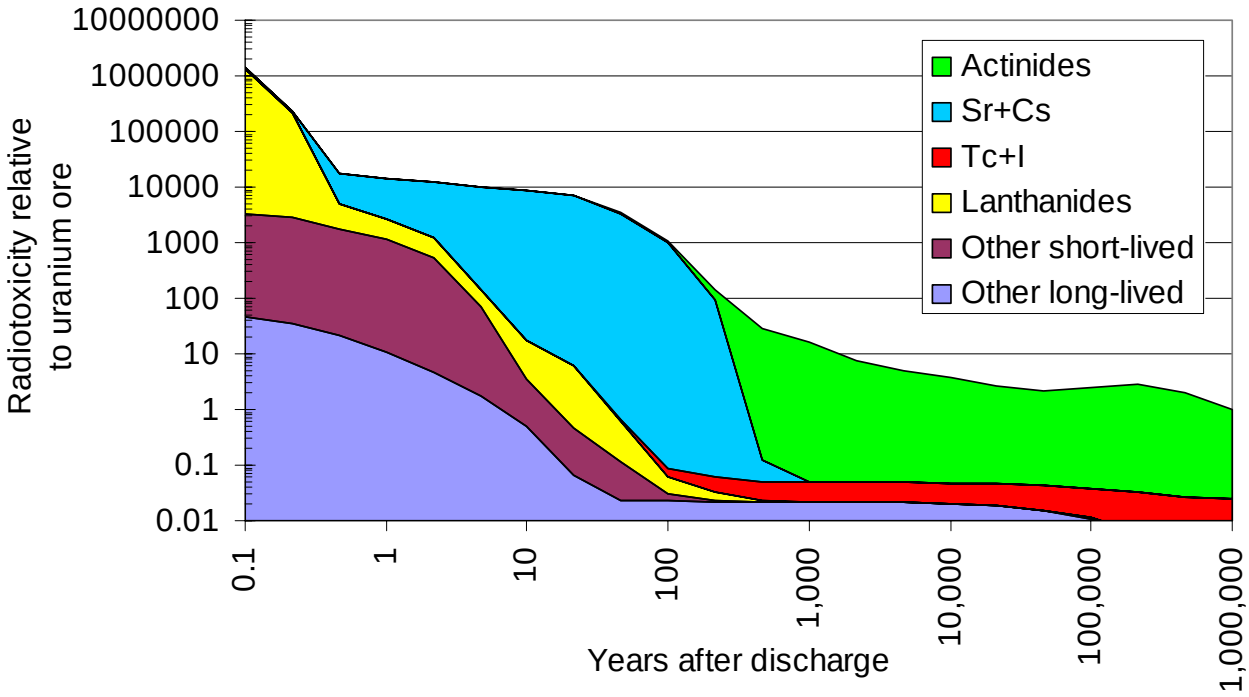

Figure B-3. Radiotoxicity of used fuel relative to uranium ore.

Next, consider how to "peel back the onion," to reduce the amount and longevity of radiotoxicity. The first step is to remove the uranium and transuranic elements (actinides), these can be fissioned to produce energy. Thus, proper use of technology can turn them from waste liabilities into energy assets. Figure B-4 shows the result. If the energy content elements are indeed removed from waste, the waste is less radiotoxic than uranium ore in less than 1,000 years. Humans have successful engineering experience with this time scale and thus convincing waste disposal assessments should be easier to do than for 1,000,000 time periods.

In the first few decades, the radiotoxicity is dominated by cesium and strontium (Cs137 and Sr90), which have about 30-yr half-lives. Most AFCI recycle strategies call for these elements to be removed from the other fission products and managed separately due to their high heat production as they decay. Figure B-5 shows the result. The radiotoxicity of the residual long-term waste falls below uranium ore in less than 100 years. Basically, separation of Cs-Sr divides the waste into an intermediate term component (Cs-Sr) that only has to be managed for a few hundred years and a residual long-term component that has relatively low long-term radiotoxicity.

[13] Calculations for used fuel with 50 MW-day/kg burnup. Other long-lived elements include selenium, palladium, tin, and antimony. All other fission products are grouped into "other short-lived" elements.

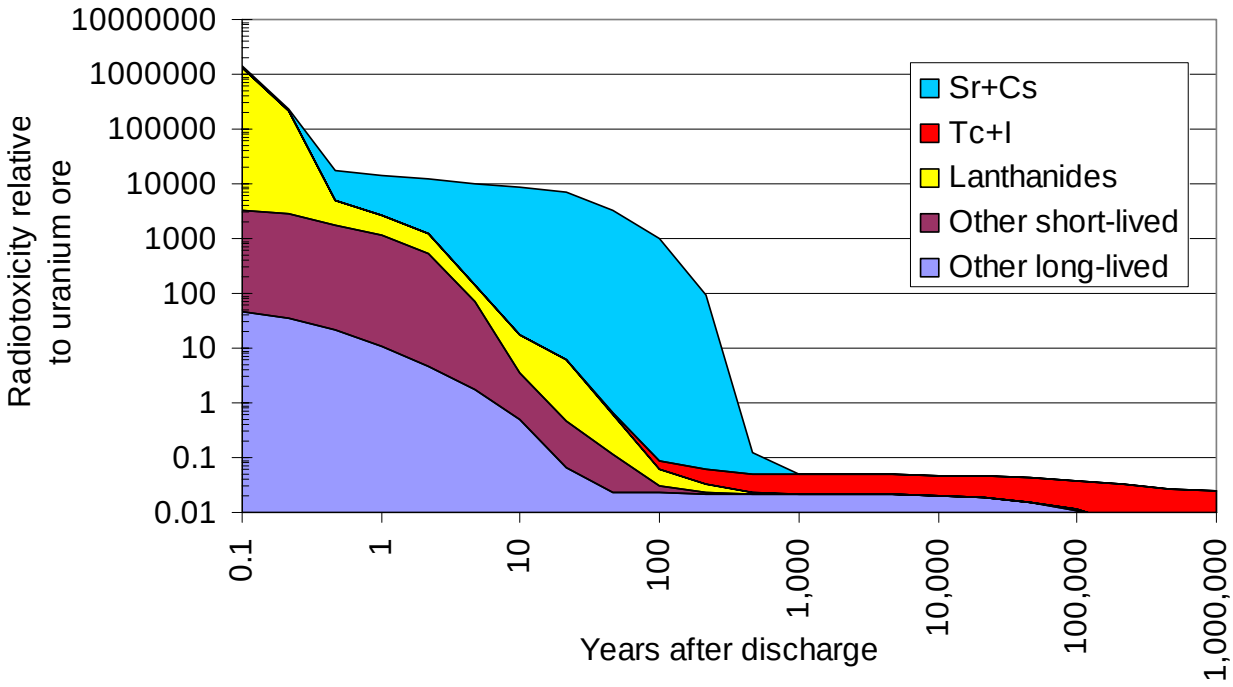

Figure B-4. Radiotoxicity of used fuel relative to uranium ore, with energy content elements removed.

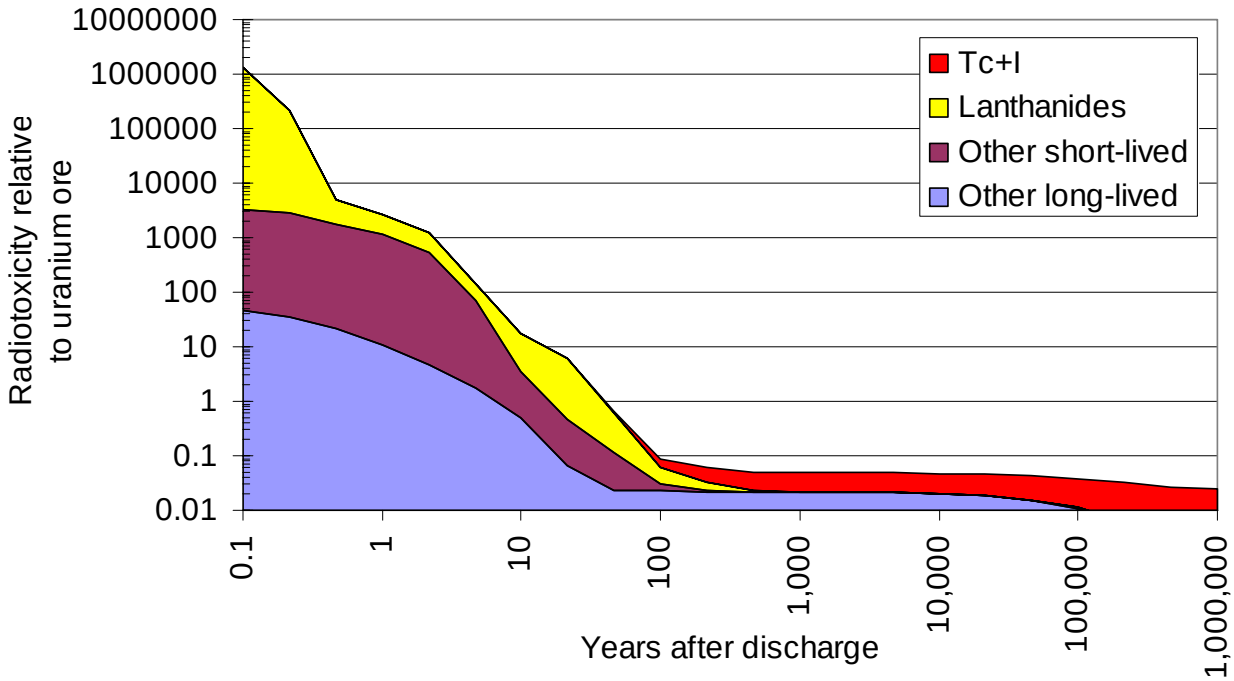

Figure B-5. Radiotoxicity of used fuel relative to uranium ore, with energy content (uranium and transuranic) and high-heat (Cs-Sr) elements removed.

Can the onion be pealed back further? Within one year after discharge from a nuclear power plant, the most toxic elements are the lanthanides, also called the "rare earths." If 99% of the energy content elements are recycled, the next most important contributors to long-term radiotoxicity are technetium (Tc) and iodine (I). Figure B-6 shows the radiotoxicity profile if the lanthanides and Tc-I are removed. The radiotoxicity of the residual wastes falls below uranium ore in less than fifty years. Since removal of the lanthanides only reduces the time scale from ~100 years to ~50 years, it would seem less likely to be warranted than removal of the TRU and Cs-Sr from residual wastes, which reduces the time scale from ~1,000,000 to ~100 years. Removal of Tc and I causes the long-lived radiotoxicity of residual material to be only a few percent of uranium ore.

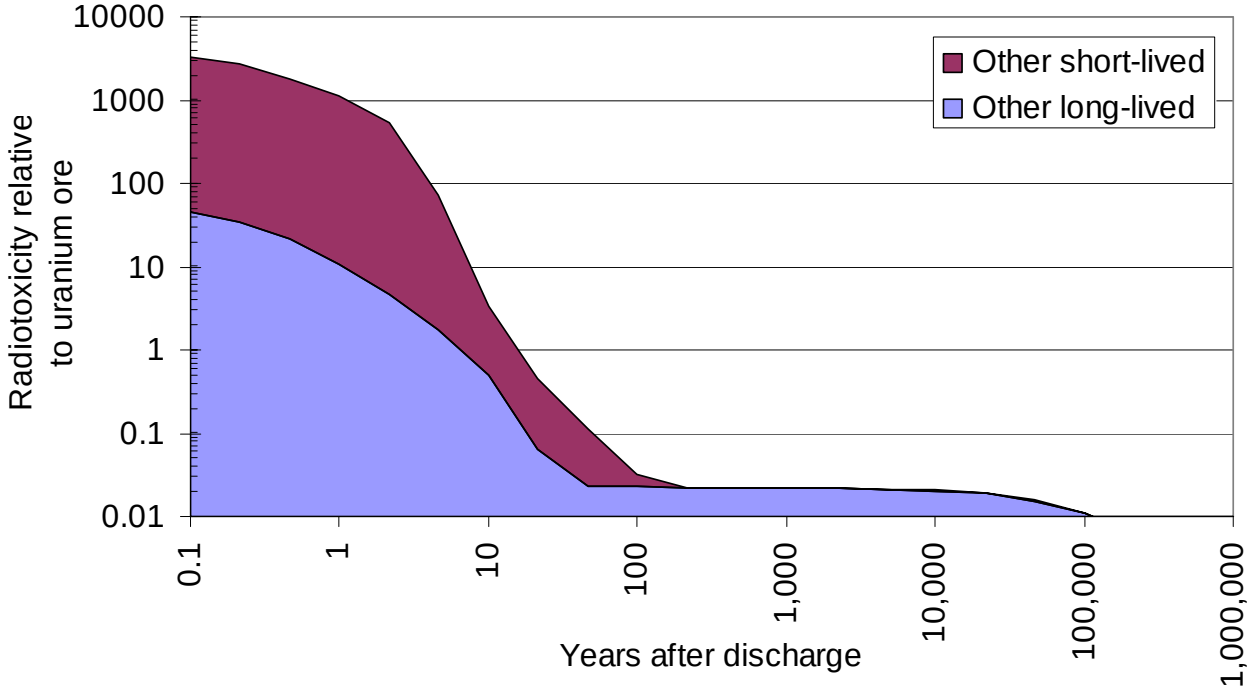

Figure B-6. Radiotoxicity of used fuel relative to uranium ore, with only residual fission products remaining. Energy elements, high-heat (Cs-Sr), lanthanides, and Tc-I are removed.

B.3 Heat Generation Rates

Like radiotoxicity, heat generation rates are important to almost any waste disposal concept. Excessive heat can lead to excessive temperatures because of the difficulty of providing for heat removal for long time periods. Only natural methods such as heat conduction or convection can be depended on for hundreds and thousands of years. This subsection shows that the same basic pattern seen for radiotoxicity – TRU, Cs-Sr, Tc-I, lanthanides, other – occurs for the heat generation rate.

There is an obvious benchmark for radiotoxicity, the radiotoxicity of natural uranium ore that starts the process. There is not such an obvious benchmark for heat generation rate because the rate of heat removal depends on how the waste disposal site is arranged and the heat conductivity

of surrounding material. But, to gain some perspective, recognize that a heat generation rate of 100 W/tonne is one incandescent light bulb generating heat for a tonne of material.

Figure B-7 shows the heat generation for used fuel. As with radiotoxicity, the most important material to remove from used fuel are the actinides, followed by Cs-Sr. Figure B-8 shows the heat generation rate after the energy content (uranium, transuranics) and high-heat elements (Cs-Sr) are removed from residual waste.

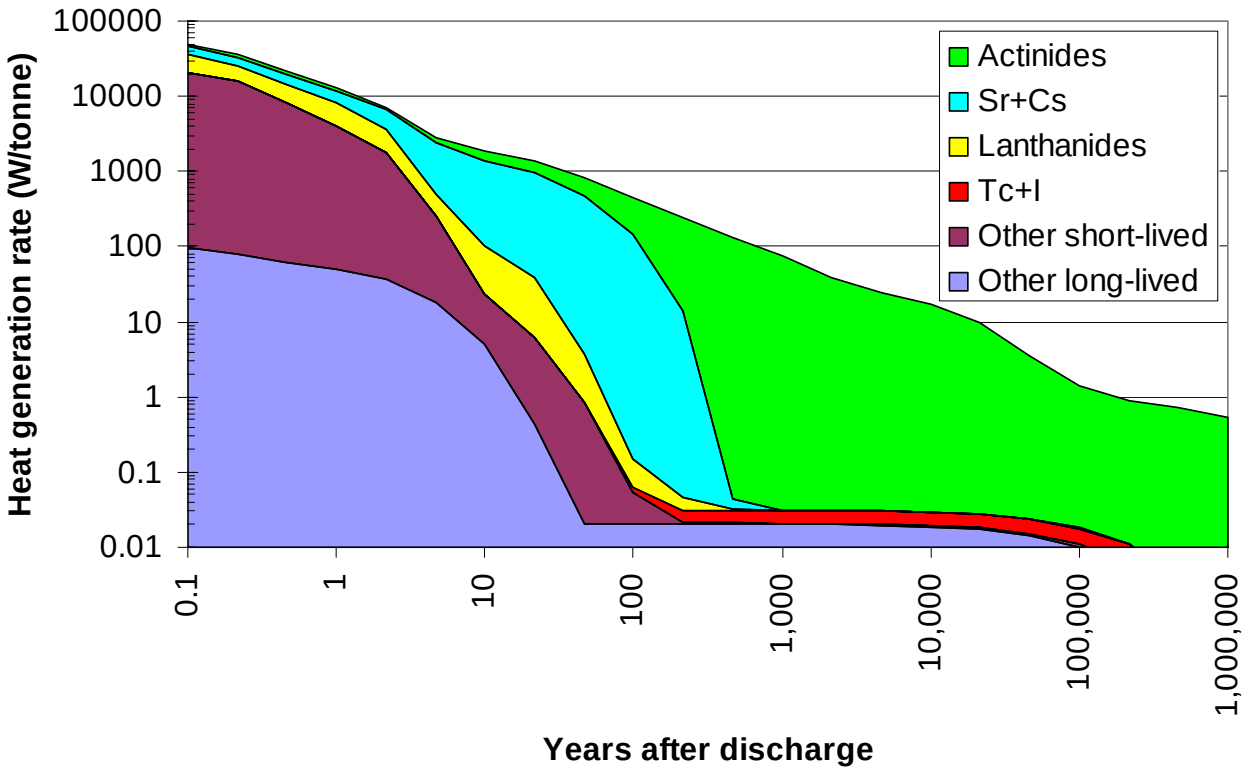

Figure B-7. Heat generation rate of used fuel.

One could go further and remove the lanthanides and Tc-I, but figure B-8 shows that the heat generation rate would not be greatly reduced.

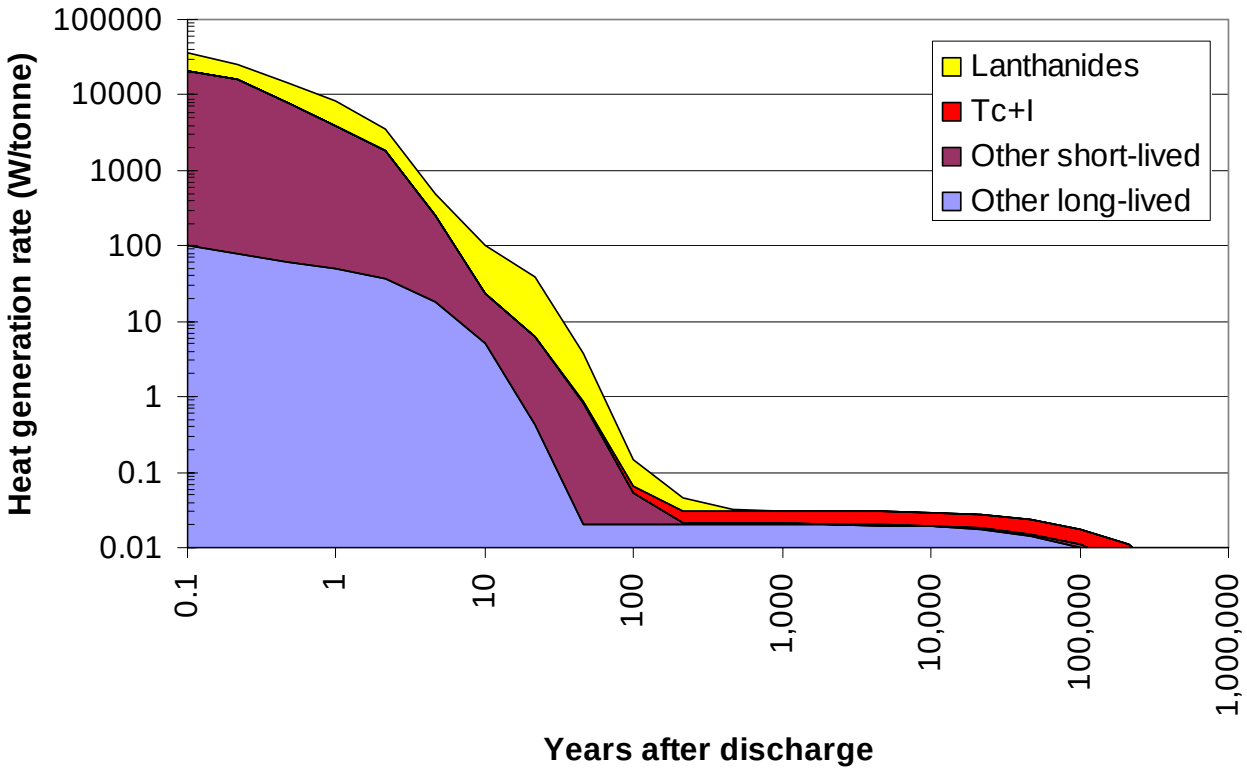

Figure B-8. Heat generation rate of used fuel with energy content (uranium, transuranic) and high heat-load elements (Cs-Sr) removed.

B.4 Potential Repository Constraints

Radiotoxicity and heat generation rates are useful metrics, but do not, by themselves, indicate the risk and cost of disposal of used nuclear fuel or residual wastes. These require looking at specific proposals for waste disposal in actual candidate sites. No country yet has a repository in operation for used nuclear fuel, and therefore there are no hard numbers for the risk and cost of used fuel disposal. The preceding discussion does suggest that the sequence of removing material from residual waste should be the energy content elements (uranium and transuranics), Cs-Sr, and then either lanthanides or Tc-I depending on whether the objectives are short-term or long-term.

The U.S. proposes to dispose of used fuel in a geologic repository at Yucca Mountain, Nevada. Examination of some of the constraints on such disposal helps us look deeper at how recycling can address waste management challenges.

There are four potential constraints – legislative capacity limits, waste volume, waste heat, and hypothetical dose via groundwater if the waste escapes from the repository. The application of these constraints to fuel cycle assessments depend on national regulations and waste site specifics. Yet, just as for the simple radiotoxicity and heat generation calculations (section B.3), the most important components of used fuel are uranium, transuranic elements, cesium-strontium, and technetium-iodine. The relative contribution of these four components depend on the metric used.

The **legislative mass limit** for the Yucca Mountain repository is 70,000 tonnes; 7,000 of which are reserved for defense wastes. This limit is defined by the amount of "initial heavy metal," that is, the amount of heavy metal, such as uranium, that is used to start the process. The "initial heavy metal" mass is thus the mass of uranium in fresh fuel, which in turn equals the total of uranium, transuranics, and fission products in discharged fuel. Since uranium is ~94% of the discharged fuel, if uranium is removed for future use, the measurement of residual waste mass varies by a factor of twenty if the unit is "initial heavy metal" versus the actual final waste mass. (The actual final waste mass if 5% of the total; the "initial heavy metal" is 100% of the total.) A comprehensive advanced fuel cycle policy would address this, preferably by changing the definition of capacity from "initial heavy metal" to the amount actually disposed.

The **volume of waste** is determined by the mass of material to be disposed times the concentration of waste in the final waste form, adjusted to reflect the volume of surrounding waste packing. For example, one potential waste form is borosilicate glass. For each material to be put into such a waste form, there is a maximum concentration that will dissolve into the glass, which determines the maximum waste loading. The glass is then put into some sort of package. Work continues on appropriate waste forms and packaging. Removal of uranium from the residual high-level waste therefore both recovers energy content and helps reduce the mass and volume of residual high-level waste. The high-level waste volume is also reduced by keeping long-lived contaminants (such as technetium and iodine) out of specific products such as uranium, transuranic elements, and Cs-Sr so that they can be either consumed or disposed in ways other than high-level waste.

The **heat generated by waste** must be factored into the selection and design of the waste form, waste packaging, and waste site. The temperature of wastes may increase depending on the detailed design, yet waste forms and packages must maintain their integrity and the performance of the waste site must not be compromised. For a repository similar to the Yucca Mountain site, analyses have shown that the heat generated from the time the repository is closed (ventilation stops) to about 1500 years helps compare options. Figure B-9 shows the contributors to this time-integrated "heat commitment" from used LWR fuel. Plutonium and americium (and their decay daughters) comprise about 90% of the heat commitment; thus, to reduce the "heat commitment" by a factor of ten requires removal of plutonium and americium (and their decay daughters). Note that the single most important isotope is Am241. Its contribution to heat in the 50-1500 year time period is reflected in two slices in figure B-9, plutonium (which includes Pu241 that decays into Am241) and americium (which includes Am241). The partition between plutonium and americium depends on the age of the used fuel because of the decay of Pu241 (14.4-year half-life) into Am241. With 5-year old fuel, plutonium and its daughters (such as Am241) are about three-quarters of the heat commitment; material that starts as americium and its daughters is about 15%. As the fuel ages, the plutonium fraction decreases and the americium fraction increases. The next most important heat generators are cesium and strontium, bringing the total heat commitment to about 99%, so that removal of the transuranics, cesium, and strontium reduces the heat by a factor of 100. Detailed calculations validate this.[Wigeland2006]

Figure B-9. Heat to repository during key time period (50-1500 yr) from elements in 5-yr old fuel.

The **hypothetical dose via groundwater exposure** depends on a host of factors and complex modeling of the repository site and waste behavior. Past calculations for the Yucca Mountain repository [Halsey2005] were scaled for fuel cycle assessments. Figure B-10 shows the relative contribution to hypothetical peak dose, which occurs about a half-million years after discharge from the reactor. Uranium and transuranic elements and their daughters comprise about 99% of the potential dose at ~500,000 years. The single most important isotope is Np237, which is a daughter of both Pu241 and Am241. Thus, the contribution to future Np237 dose is reflected in three slices of figure B-10, Np itself, the amount of Pu that decays into Np237, and the amount of Am that decays into Np237. The relative contributions are graphed this way because it shows which elements have to be separated at about 5 years after reactor discharge.

Detailed, independent analyses [Wigeland2005, Wigeland2006b] show the same trend. Figure B-11 shows the estimated offsite dose rate for the assumed case of direct disposal of 70 tonnes of initial heavy metal of used PWR fuel in the Yucca Mountain repository, normalized to the peak dose rate.[Wigeland2006b]

Figure B-10. Hypothetical peak dose at ~500,000 yr via ground water from geologic repository from elements in 5-year old fuel.

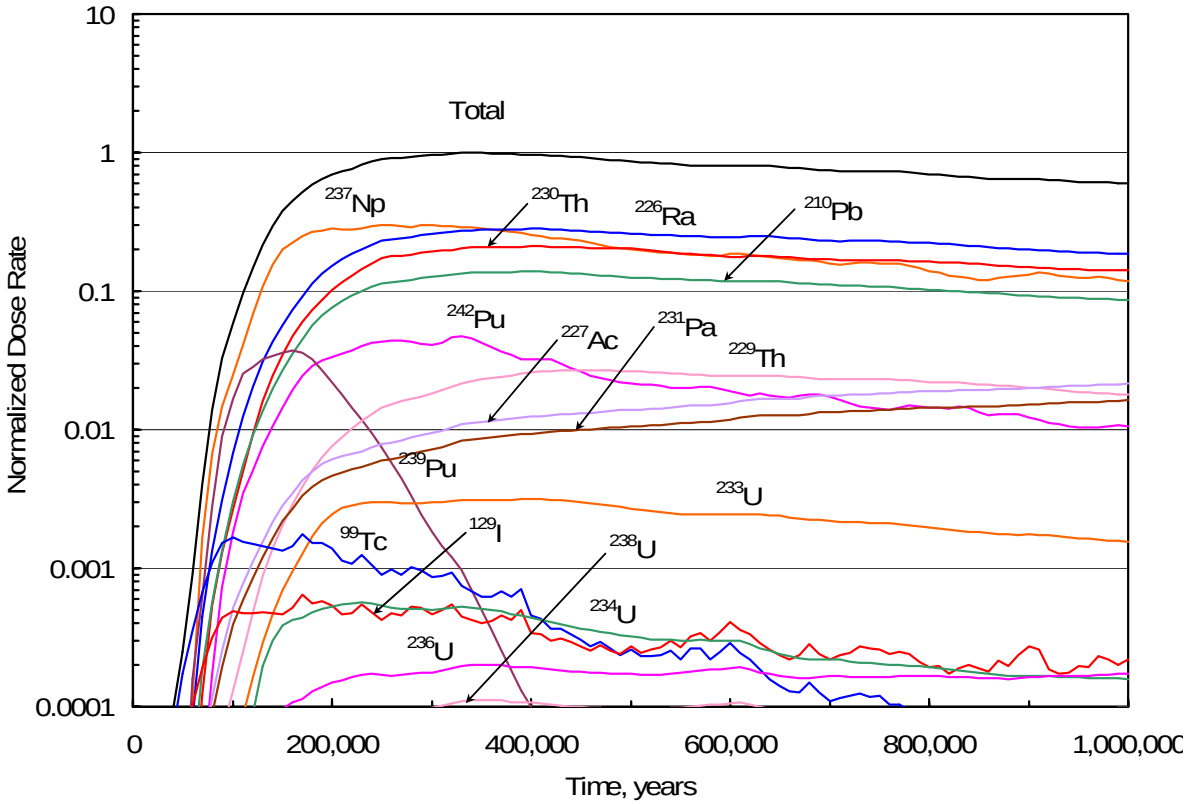

Figure B-11. Estimated offsite dose rate of 70,000 tonnes of used PWR fuel, normalized to the peak dose rate.[Wigeland2006b]

Figures B-1 through B-10 incorporate radioactive daughters with the parent isotope. Figure B-11 shows each isotope at the time of hypothetical offsite exposure.

At the time of exposure, in the 4n+1 decay chain, the isotopes initially present in used fuel (Np237, Pu241, Am241, etc.) have decayed into Np237, U233, and Th229 in the figure. Of these Np237 is the most important; recall it arises from Np, Pu, and Am in disposed fuel.

Reducing the hypothetical Np237 dose after hundreds of thousands of years requires recycle of Np, Pu, and Am before disposal.

Next, consider the 4n+2 decay chain. The isotopes initially present in used fuel (U234, U238, Pu238, Pu242, etc.) have decayed into U238, Th230, Ra226, and Pb210. Of these, the most important in figure B-11 are Th230, Ra226, and Pb210. Note at the time of disposal, the mass of transuranics in used LWR fuel in this decay chain is small relative to uranium (U238). Thus, reducing the hypothetical Th230/Ra226/Pb210 dose after hundreds of thousands of years requires recovery of uranium before disposal.

The next most important decay chain in figure B-11 is 4n+3. It provides Pu239, Pa231, and Ac227 in the figure. Pu239 arises from Pu239 itself, Am243, etc. Pu239 decays into U235, which leads to Pa231 and Ac227. Reducing the hypothetical Pu239/Pa231/Ac227 dose after hundreds of thousands of years requires recovery of uranium and plutonium before disposal.

The 4n decay chain is the least important in figure B-11, only U236 appears.

So, working through the four decay chains leads to the conclusion (consistent with figure B-10) that uranium, neptunium, plutonium, and americium must be recovered; they are the dominant sources of the isotopes that can lead to offsite repository doses hundreds of thousands of years in the future. Table 1 of [Wigeland2006b] indicates that recovery and consumption of only three of these four elements only reduces peak dose by 10x.

U, Pu, Am gives 10.9x
U, Np, Pu gives 6.13x
U, Am, Np gives 1.43x
Pu, Np, Am gives 1.50x

However, recovery and consumption of all four elements (U, Np, Pu, Am) reduces peak dose by a factor of 91x. That is, these four elements comprise 99% of the problem, precisely matching figure B-10.

The higher transuranic elements (Cm, Bk, Cf) are less important because they are not the major sources of the key isotopes Np237/U233 (4n+1), U238 (4n+2), Pu239/U235 (4n+3), and U236 (4n).

Tc-99 and I-129 are well below 0.01 (1%) in figure B-11; why are they important? They are the other 1% of the problem because the time of peak dose shifts from ~300,000 years to ~100,000 years, as shown in figure B-12. Now, Tc-99 is indeed ~1% of the peak dose after removal of 99.9% of all transuranic elements and uranium. The 1% value matches figure B-10.

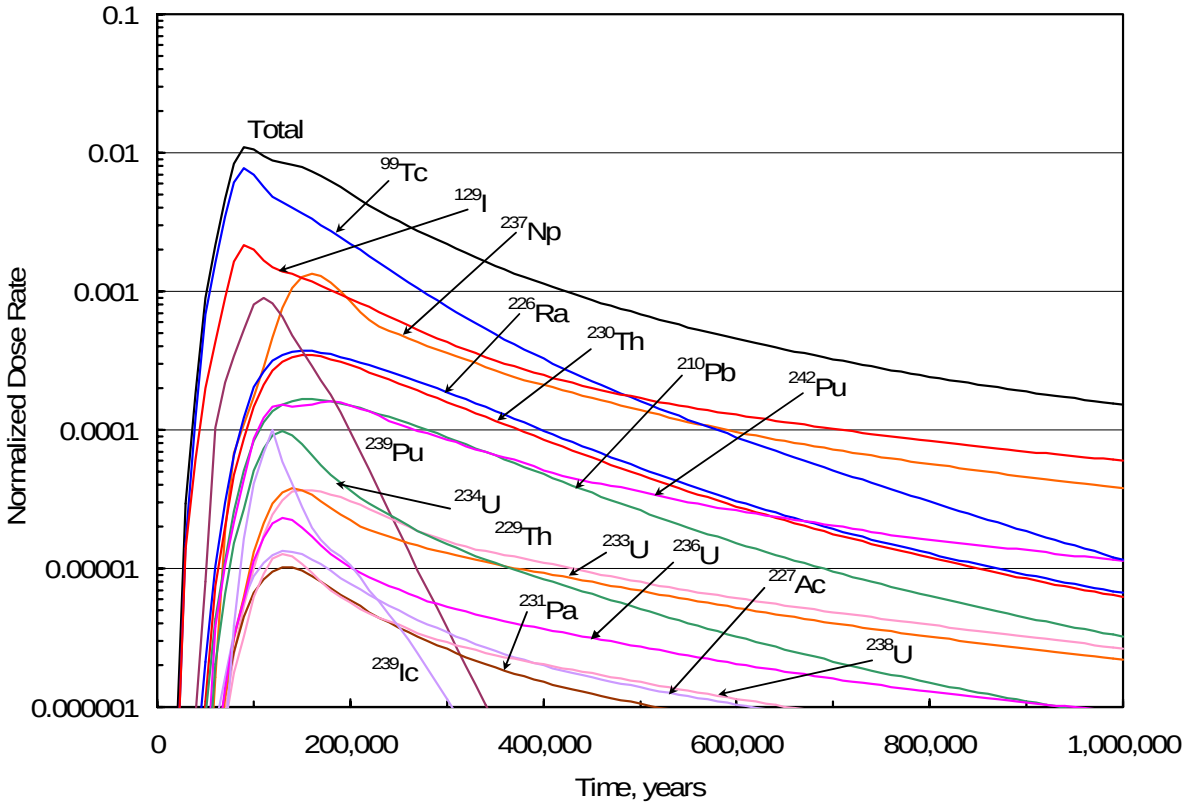

Figure B-12. Estimated offsite dose rate of 70,000 tonnes of used PWR fuel after 99.9% of uranium and transuranic elements are removed, normalized to the peak dose rate for direct disposal of used PWR fuel.[Wigeland2006b]

B.5 Summary

Whereas recycling for energy content necessitates attention to only plutonium and uranium, recycling for U.S. waste management can include the following:

- Recovery and consumption of transuranic elements, turning waste management liabilities into energy assets
- Eventual reuse of uranium, when uranium ore prices warrant
- Separate management of the heat from intermediate-lived cesium and strontium to simply the design of disposal of residual long-lived wastes.
- Durable waste forms for the residual wastes, as appropriate.

Such approaches can lead to the following:

- Residual waste mass reduced by an order of magnitude.
- The waste volume reduction depends on waste form and waste package selections.
- Residual heat commitment to the repository reduced by two orders of magnitude.
- Residual hypothetical dose from waste emplaced in the repository apparently[14] reduced by two orders of magnitude.
- Radiotoxicity of residual waste less than uranium ore in less than 1,000 years.

[14] There are non-linearities in the calculation of hypothetical dose from the repository. Thus, reducing the source term by two orders of magnitude may not result in the same reduction in estimated dose.

Appendix C. Parameters Used in Dynamic Analyses

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Selection of parameters for the analyses in section 5 is not intended to define a specific case; rather, most have been selected to most clearly illustrate behavior of the options. Where possible, these parameters were also used in section 4 analyses. First, Table C-1 lists parameters common to all fuel cycle options.

Table C-1. Parameters Common to All Fuel Cycle Options

Parameter	Unit	Value
Overall time line These values are from DOE as of February 2007.		
Nuclear energy growth rate	%/year	2.25%
Year first LWR comes on line	Date	2015
Year Advanced Fuel Cycle Facility comes on line	Date	2016
Year first UREX+ separation facility comes on line	Date	2020
Year first fast reactor comes on line	Date	2021
Initial LWR fleet These parameters match the U.S. fleet after Browns Ferry returns to service in early 2007.		
Nuclear power plant capacity in 2000	GWe	100
Nuclear plants in 2000	#	104
Retirement of initial LWR fleet These parameters are very close to the retirement profile that results if every U.S. reactor lifetime is extended from 40 to 60 years.		
LWR retirement start	Date	2027
LWR retirement end	Date	2048
LWR retirement duration	Date	21
Legacy fuel parameters These parameters match the Nuclear Regulatory Commission (NRC) database for the total LWR fuel in 2000 (43 kt).		
Initial LWR fuel low burnup (1968-2000)		
average burnup	GWth-day/t	33
Total LWR legacy SNF in 2000	kt	43
LWR parameters These parameters approximate the behavior of current LWRs and match the existing fleet.		
LWR capacity factor	%	90%
LWR thermal efficiency	%	34%
Average LWR size (calculated from other parameters)	GWe	1.0684
Average LWR size (user input)	GWe	1.0700
Average LWR size (calculated from other parameters)	GWth	3.1471
LWR burnup		
Initial LWR burnup in 2001	GWth-day/t	51

Table C-1. Common Parameters (Continued)

Parameter	Unit	Value
LWR time-related parameters Illustrative values, generally optimistic, e.g., a minimum wet storage time of 5 years may not be adequate for fuel to cool adequately to transport to the separation facility.		
LWR licensing time	years	1
LWR construction time	years	4
LWR lifetime	years	60
LWR wet storage time	years	5
LWR dry storage time	years	5
LWR enrichment time	years	1
LWR fabrication time	years	0.5
LWR reprocessing time	years	0.5
Number of batches	#	5
LWR cycle length	years	1
Fuel residence time (calculated)	years	5
Advanced Burner Reactor (ABR) parameters A conversion ratio of 0.25 was used because there are more cases available at that conversion ratio, UOX to fast reactor, MOX to fast reactor, and IMF to fast reactor.		
ABR conversion ratio	#	0.25
ABR capacity factor	%	85%
ABR thermal efficiency	%	36%
ABR burnup	GWth-day/t	172
Average ABR size	GWe	0.36
Average ABR size	GWth	1.00
ABR time-related parameters These are basically the same as for LWRs in lieu of better information.		
ABR licensing time	years	1
ABR construction time	years	4
ABR lifetime	years	60
ABR wet storage time	years	5
ABR dry storage time	years	5
ABR fabrication time	years	0.5
ABR reprocessing time	years	0.5
Number of batches	#	7.3
Cycle length	years	0.43
Fuel residence time (calculated from other parameters)	effective full power years	3.16

Table C-1. Common Parameters (Continued)

Parameter	Unit	Value
Repository parameters Current DOE values.		
Repository opening date	Date	2017
Repository filling rate	kt/year	0.4 year-1, 0.6 year-2, 0.12 year-3, 0.2 year-4, 0.3 thereafter so that 63 kt is emplaced by about 2039
Amount sent to repository and not retrieved	kt	63

Figure C-1 shows retirement profiles for the current 104 U.S. nuclear power plants. The curves marked "2002 NRC data" [green] and "2006 NRC data" [black] denote when the fleet would retire based on only license extensions granted by those dates, using data from www.nrc.gov. If all renewal applications submitted as of November 2006 are approved (as is expected), the retirement profile shifts to "if current reviews ok" [yellow]. Utilities have told the NRC of plans to submit several additional renewals; if they are all approved, the retirement profile shifts to "if planned submittals ok"[15] [blue] If all plants are extended to 60 years, one obtains the "if all plants extended" profile [red].

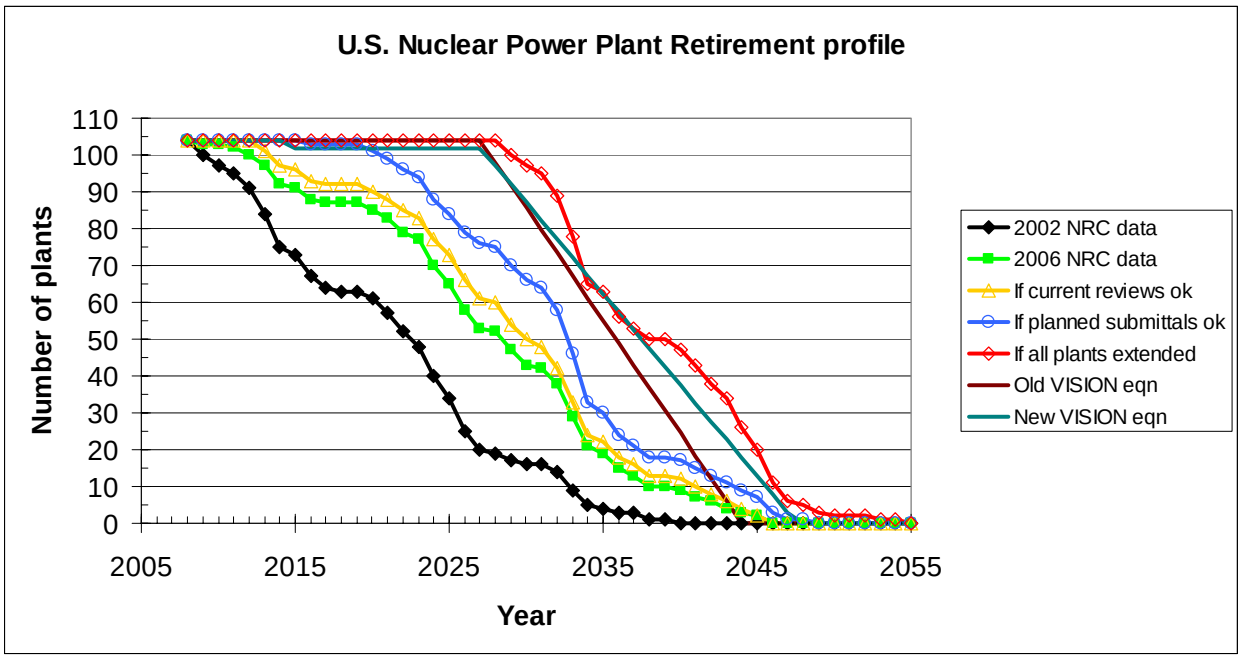

Figure C-1. U.S. nuclear power plant retirement profile for the current 104 plants.

[15] There are also 12 additional renews planned (per utility statements to NRC) but the exact plants have not been specified. So, the best description of current plans would be a bit to the right of the blue curve.

The old straight-line retirement profile [brown] embedded in VISION (and DYMOND before that) is too conservative and out of date. Furthermore, when running cases with zero percent nuclear growth, the straight-line curve or indeed the "all plants extended" curve do not allow any new power plants until after 2035 because no plants would have retired and no additional nuclear energy is allows for no-growth cases.

For these reasons, VISION is shifting to a "hockey stick" shape retirement profile model.[cyan]

Date of phase-A start (default = 2017)
Percent of legacy reactors retired in phase-A (default = 2%)
Date of phase-B start (default = 2027)
Duration of phase-B (default = 21 years)

The use of Phase-A allows VISION to build a couple of reactors relatively early, even at zero nuclear growth. It reflects the possibility that a few of the existing 104 reactors will not be extended. Phase-B does a good job of matching the "all extended" profile. Of course, the user can adjust the parameters to the previous VISION algorithm if desired.

Table C-2 provides the parameters for how fast reactors are to be built. There are two sets of parameters controlling ABR growth because different models require different types of units. The two sets are meant to produce the same results. The system dynamic model VISION requires the user to input the percent of new construction in each 5-year time period that would be **ordered** as fast reactors (or other types of reactors); this focuses on a decision that must be made years before the effect. Other models require the user to indicate how many GWe of ABRs are to **come on line** in a given year. This approach is easier to understand.

The set of parameters in Table C-2 are for GNEP, i.e., no thermal recycling. For cases where 1 pass of IMF or MOX is used before recycle in fast reactors, the parameters in Table C-2 are shifted 20 years later and sometimes adjusted slightly.

Table C-2. Parameters Specifying Growth of Fast Reactor Capacity

ABR growth parameters		
ABR first possible date comes on line	yr	2021
If input in the form of GWe to come on line in a given time period, per B. Dixon.		
ABR come on line (Gwe) 2020-2024	GWe	0.36
ABR come on line (Gwe) 2025-2029	GWe	0.00
ABR come on line (Gwe) 2030-2034	GWe	5 = 5 x 1 Gwe/yr
ABR come on line (Gwe) 2035-2039	GWe	10 = 5 x 2 Gwe/yr
ABR come on line (Gwe) 2040-2044	GWe	10 = 5 x 2 Gwe/yr
ABR come on line (Gwe) 2045-2049	GWe	Limited only by fuel supply
If input in the form of fraction of new reactors ordered that should be ABRs		
Max percent ABR ordered 2015-2019	%	0.5%
Max percent ABR ordered 2020-2024	%	0.0%
Max percent ABR ordered 2025-2029	%	5.0%
Max percent ABR ordered 2030-2034	%	20.0%
Max percent ABR ordered 2035-2039	%	20.0%
Max percent ABR ordered 2040-2044	%	Limited only by fuel supply
Max percent ABR ordered 2045-2049	%	Limited only by fuel supply

Table C-3 provides the parameters for how UREX+ separation capacity grows. (The separation capacity for used fast reactor fuel is considered separately and is assumed to match the growth of fast reactors.) These are approximate parameters that serve as the starting point for analysis, the actual UREX+ separation capacity is adjusted by the user such that there is little or no excess separation capacity throughout the century while also reducing the stored inventory near zero by 2100.

Table C-3. Parameters Specifying Growth of Separation Capacity

UREX+ capacity (LWR separation cap) The first full scale plant are assumed to have 5-year rampup schedules. Later plants are assumed to have 3-yr rampup schedule. In VISION, the separation plants have to be ordered 5 years before the following dates.	**Unit**	**Value**
UREX+ separation start	yr	2016=AFCF 2020=full scale plant
UREX+ capacity 2015-2020	kt/yr	Average=0.1 Starting in 2016, rampup of 0.1 the first three years, then 0.2, to get sufficient separated TRU to start first ABR in the model.
UREX+ capacity 2020-2024	kt/yr	Average=1.8 Starting in 2020, 5-yr rampup to 3 kt/yr (20%)
UREX+ capacity 2025-2029	kt/yr	3.0
UREX+ capacity 2030-2034	kt/yr	3.0
UREX+ capacity 2035-2039	kt/yr	3.0
UREX+ capacity 2040-2044	kt/yr	3.0
UREX+ capacity 2045-2049	kt/yr	3.0
UREX+ capacity 2050-2054	kt/yr	Average = 5.2 Starting in 2050, 3-year ramp from 3 to 6 kt/yr
UREX+ capacity 2055-2059	kt/yr	6.0
UREX+ capacity 2060-2064	kt/yr	6.0
UREX+ capacity 2065-2069	kt/yr	6.0
UREX+ capacity 2070-2074	kt/yr	6.0
UREX+ capacity 2075-2079	kt/yr	6.0
UREX+ capacity 2080-2084	kt/yr	Average = 8.2 Starting in 2080, 3-yr ramp from 6 to 9 kt/yr
UREX+ capacity 2085-2089	kt/yr	9.0
UREX+ capacity 2090-2094	kt/yr	10.0
UREX+ capacity 2095-2099	kt/yr	12.0
UREX+ capacity 2100	kt/yr	14.0

Table C-4 provides the parameters differentiating among cases in section 5.

Table C-4. Parameters Specifying Growth of Separation Capacity for Alternative Cases

Case	Multipass MOX	Multipass IMF	UOX to fast reactor (GNEP)	1-pass MOX then fast reactor	1-pass IMF then fast reactor
Date first thermal recycle occurs	2020		N/A	2020	
Conversion ratio of fast reactor	N/A		0.25	0.25	
Date that first fast reactor comes on line	N/A		2021	2040	